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CONSTRUCTION PRODUCTIVITY ADVANCEMENT RESEARCH (CPAR) PROGRAM

Cavitation- and Erosion-Resistant Thermal Spray Coatings

by

Jeffrey H. Boy, Ashok Kumar,
Patrick March, Paul Willis, and Herbert Herman

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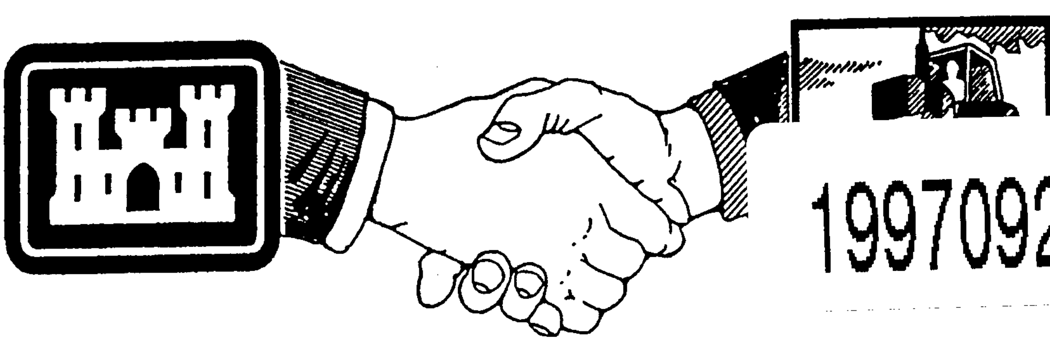

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13. ABSTRACT (Maximum 200 words)
This study demonstrated the effectiveness of thermal spray cavitation- and erosion-resistant metal coatings for hydroelectric and utility plant turbines and pumps. Of 21 thermal spray coatings tested, Stellite® 6 applied by the high-velocity oxyfuel (HVOF) process had the lowest cavitation rate (11.7 mg/h). This was higher than the corresponding rate of 3.2 mg/h for 308 stainless steel weld reference. In slurry erosion wear testing, the volume loss for HVOF-applied Stellite® 6 was 5.33 mm3/h, much lower than volume losses for 304 stainless steel and A572 carbon steel. The field applicability of Stellite® 6 was successfully demonstrated on a hydroelectric pump/turbine.

Stellite® 6 deposited by the HVOF process should be considered for repair of damage resulting from erosion and subsequent cavitation caused by surface roughening. Stellite® 6 coatings should also be considered for the mitigation of galvanic corrosion. Damage caused by direct cavitation should be repaired by welding. Advanced iron-based alloys such as NOREM®, D-CAV®, CaviTec®, and Hydroloy® should be considered for use due to their superior cavitation resistance. The use of thermal spray coatings such as HVOF-applied Stellite® 6 should also be considered for repair of pumps subjected to erosion and subsequent cavitation caused by surface roughening.

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Foreword

This study was conducted for the Directorate of Civil Works, Headquarters, U.S. Army Corps of Engineers (HQ USACE) under Construction Productivity Advancement Research (CPAR) Work Unit 3121-LY4, "Development of Cavitation/Erosion-Resistant Thermal Spray Coatings." The technical monitors were A. Wu, CECW-EE, and C. Chapman, CECW-OM.

The work was performed by the Materials Science and Technology Division (FL-M) of the Facilities Technology Laboratory (FL), U.S. Army Construction Engineering Research Laboratories (USACERL) in partnership with the Thermal Spray Laboratory at the State University of New York (SUNY) at Stony Brook. Flame Spray Industries, Fort Washington, NY, was a participant in the research. The USACERL Principal Investigator was Dr. Ashok Kumar. Dr. Jeffrey H. Boy is at USACERL under a postgraduate research program through the Oak Ridge Institute for Science and Education, Oak Ridge, TN. Patrick March is Manager, Engineering Laboratory of the Tennessee Valley Authority (TVA), Norris, TN. Paul Willis is with the USACE Hydroelectric Design Center (CENPD-PE-HD), Portland, OR. Dr. Herbert Herman is the director of the Thermal Spray Laboratory at SUNY Stony Brook. Thermal spray samples were prepared by the Zatorski Coating Co., East Hampton, CT, and weld samples were prepared by Robert A. Weber, CECER-FL-M. The field demonstration was conducted at the TVA Raccoon Mountain pumped-storage hydroelectric plant, Chattanooga, TN, with the cooperation of Mitch Burress, Wayne James, and Leon Hicks. The draft Civil Works Guide Specification was prepared by Steve Dingman, U.S. Army Engineer District, USACE Portland. Sam Testerman, Portland District, reviewed the safety and occupational health elements of the report. Dr. Ilker Adiguzel is the Acting Chief, CECER-FL-M, and Donald F. Fournier is Acting Operations Chief, CECER-FL. The USACERL technical editor was Gordon L. Cohen, Technical Information Team.

Dr. Michael J. O'Connor is the Director of USACERL.

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1 Introduction

Problem Statement

The term *cavitation* refers to the formation and collapse of vapor bubbles or cavities in a fluid, generally due to localized reductions in the dynamic pressure. The collapse of vapor cavities can produce extremely high pressures that frequently damage adjacent surfaces and cause material loss. Cavitation is a major problem for the operation of hydraulic equipment such as hydroelectric turbines, valves and fittings, flow meters, hydrofoils, pumps, and ship propellers. Cavitation frequently contributes to high maintenance and repair costs; revenue lost due to downtime and cost of replacement power; decreased operating efficiencies; and reduction of equipment service life (March and Hubble 1996). The most commonly used method for cavitation repair is the fusion process (i.e., welding). This method involves removing material from the damaged areas and filling the space by welding. The most widely used filler materials are 308L or 309L stainless steel (Ruzga, Willis, and Kumar 1993). Extensive weld repair can introduce stresses in the area being repaired and can damage the component.

A preventive maintenance approach making use of cavitation-resistant coatings has the potential to substantially reduce the costs noted above and greatly reduce the need for welding-type repairs. The U.S. Army Construction Engineering Research Laboratories (USACERL) initiated a Cooperative Research and Development Agreement (CRDA) under the Corps of Engineers Construction Productivity Advancement Research (CPAR) Program to investigate the effectiveness of thermally sprayed alternative coatings in reducing cavitation and erosion. The CPAR-CRDA partner was the Thermal Spray Laboratory, State University of New York (SUNY), Stony Brook, NY.

Objective

The objective of this research was to demonstrate the effectiveness of innovative non-fusion thermal spray cavitation- and erosion-resistant coatings for hydroelectric and utility plant turbines and pumps. The research objective

included the selection of special coating materials and development of detailed thermal spray processing techniques.

Approach

The approach was specified in the CPAR Research, Development, Commercialization Plan (RDCP) and consisted of the following six tasks:

Task 1: Preliminary Materials Evaluation. A list of candidate cavitation/erosion resistant coatings that could be thermally sprayed by high velocity oxyfuel (HVOF) and plasma spray was prepared by SUNY. The list consisted of three types of materials: Tribaloys (T-700, T-800, and T-400), Stellite (cobalt-based and nickel-based) and tungsten carbide. SUNY was to conduct preliminary laboratory screening using the ultrasonic vibratory horn to determine the optimum (HVOF and plasma) spraying parameters for up to 12 materials.

The results of these evaluations were to be used as a guide to determine the most effective means for cavitation/erosion-resistant coating repair using thermal spray. The technical and economical aspects of current repair/maintenance materials were to be studied for cost/performance comparison. The Corps of Engineers Hydroelectric Center (HDC) was to be utilized for technical assistance. USACERL was to conduct the economic analysis and select 6 materials/processing parameter for detailed laboratory evaluation.

Task 2: Thermal Spray Processing: Equipment, Materials, and Processes. The following activities were to be conducted by SUNY: equipment evaluation/recommendations for each coating material; materials characterization including chemistry and particle size distribution of the powders; substrate surface preparation techniques; and spray process and initial optimization program.

Task 3: Deposit (Coating) Characterization, Bench Scale Tests, and Evaluation Using Statistical Process Control. USACERL was to contract the Tennessee Valley Authority (TVA) or an equivalent laboratory to test the 6 selected materials/processing systems using the cavitating jet method. SUNY was to conduct tests on the materials with special emphasis on metallography (porosity, raw material oxide content, and cracks). Mechanical properties of the deposited coating were to be determined including tensile adhesion strength, microhardness, and residual stress evaluation. Additional evaluations were to also include chemical and phase analysis.

Task 4: Field Demonstration: A field demonstration, using the best materials/ processing combination, was to be conducted on a Kaplan turbine at the Dalles Hydropower Dam, Portland District. Application procedures and materials properties were to be documented. The performance of the thermal spray coatings was to be evaluated relative to the performance of standard stainless steel weld repair.

Task 5: Commercialization/Technology Transfer. The Commercialization/Technology Transfer Plan was to be executed jointly by Flame Spray Industries, Inc., the Partner Participant, and SUNY through marketing, manufacture, distribution, and user support for the product. Flame Spray Industries, Inc. was to promote thermal spray for repair/maintenance of hydroelectric pumps and turbines. SUNY will present the research results at technical symposia and at trade shows.

2 Overview of the Problem and Repair Technology

Definitions

Some common terms are used throughout this report. Although they are discussed in detail later, the reader will find it useful to be familiar with the following definitions from the start:

Erosion: The progressive loss of original material from a solid surface due to mechanical interaction between that surface and a fluid, a multicomponent fluid, or impinging liquid or solid particles (ASTM G 73 1993). As used in this report, the term refers specifically to *slurry erosion*, which is caused when a solid surface is impinged upon by solid particles suspended in a liquid stream.

Cavitation: In the literature and the field (and in this report), erosion caused by cavitation is generally referred to simply as *cavitation*. Cavitation is the progressive loss of original material from a solid surface due to the formation and collapse, within a liquid, of cavities or bubbles (ASTM G 32 1992).

Corrosion: The deterioration of a material because of reaction with its environment (Fontana and Green 1979).

Thermal spraying: A process by which finely divided metallic or nonmetallic materials are deposited in a molten or semimolten condition on a prepared substrate to form a sprayed deposit (AWS 1991).

Welding: A metal working process in which metals are joined by heating them to the melting point and allowing the molten portions to fuse or flow together (Althouse, Turnquist, and Bowditch 1967).

Characteristics of Cavitation

The formation and collapse of vapor bubbles or cavities in a fluid can produce extremely high pressures, frequently damaging adjacent surfaces and causing material loss (March and Hubble 1996). An example of cavitation damage observed on a Francis hydroelectric turbine located at the TVA Raccoon Mountain pumped-storage plant, Chattanooga, TN, is shown in Figure 1.

Pressures greater than 100,000 psi have been measured in materials by the shock wave from cavitation bubbles (Vyas and Preece 1976). A consensus has developed that material removal by cavitation is caused by a cyclic fatigue process (Richman and McNaughton 1995). The pressures can be transmitted from the collapsing bubbles to the surface either in the form of a shock wave or by microjets, depending on the distance from the surface. The cycle of formation and collapse of the bubbles occurs at a high frequency and the dynamic stress generated can cause the damage of the material by fatigue (Schwetzke and Kreye 1996).

The basics of cavitation have been reviewed for the Electric Power Research Institute (EPRI) (Rodrigue 1986). Various factors that influence cavitation pitting include:

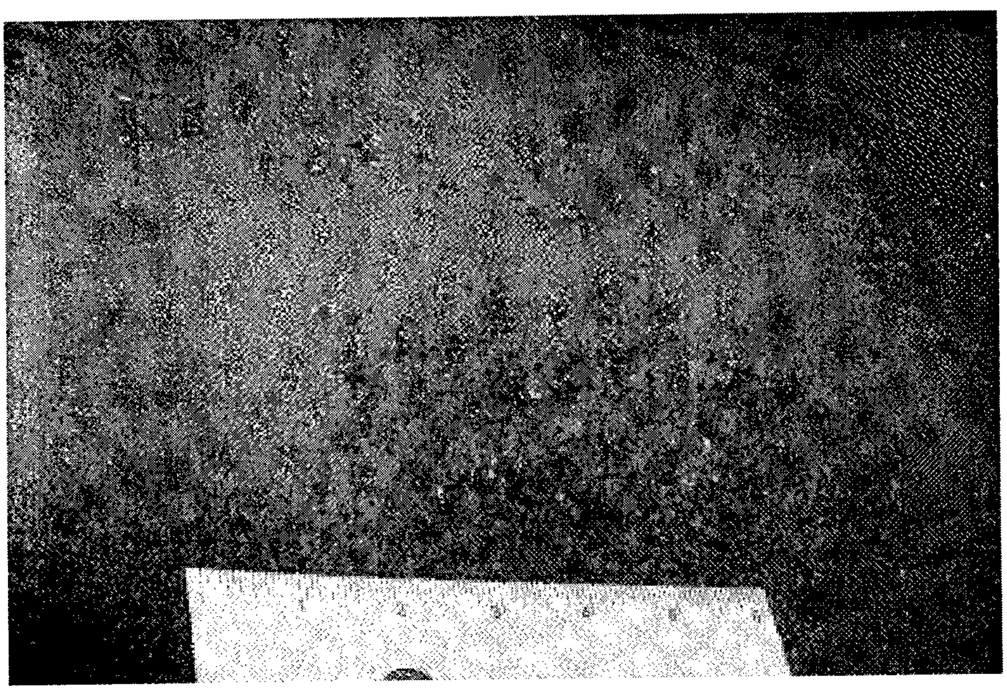


Figure 1. Cavitation damage on a TVA hydroelectric turbine blade.

- velocity effects
- material
- size effects
- corrosion
- roughness effects
- temperature effects
- thermodynamic effects
- fluid properties
- gas content.

Therefore, due to the large number of factors that influence cavitation, qualitative approaches have been developed to assist the plant manager to make cavitation repair decisions. EPRI gives plant owners several options for when to make cavitation repairs (Rodrigue 1986):

- Make all repairs during each inspection period.
- Repair only areas where cavitation damage exceeds 1/8 inch.
- Repair areas on stainless steel overlays where pitting is 1/8 inch or deeper. On carbon steel, repair areas even with light damage using stainless steel weld materials.
- Allow cavitation to progress to the maximum depth that can be repaired with two weld passes—about 3/8 inch.

Low, medium, and high cavitation have also been defined in terms of the wear rate for a normal operational year of 8000 hours. Low cavitation is defined as 1/16 to 1/8 inch-deep damage in carbon steel occurring in two year; medium cavitation is defined as more than 1/16 inch damage in austenitic stainless steel in 1 year; and high cavitation is defined as more than 1/8 inch damage in stainless steel in 6 months or less (Spicher 1994). It should be noted that repair or replacement shall be made whenever cavitation damage threatens the structural integrity of a mechanical component.

Slurry Erosion

The cavitation material-loss process usually involves erosion, but erosion may have various causes. As noted at the beginning of this chapter, for the purposes of this report the term *erosion* will refer specifically to *slurry erosion*, which occurs at a surface impinged upon by solid particles suspended in a liquid stream.

Corrosion

Corrosion occurs by an electrochemical process. Two dissimilar metals (forming an anode and a cathode), an electrolyte, and an electrical circuit connecting them are required for corrosion. Dissolution of the metal into the electrolyte occurs at the anode. Cavitation may combine with corrosion to create much greater damage rates than the sum of the two if each acted alone. Metals usually develop passive films or layers on the surface that inhibit further corrosion and metal removal. Cavitation removes this passive film exposing a fresh metal surface that can readily corrode. The increased surface roughness caused by corrosion may also promote cavitation (Rodrigue 1986).

Weld Repair

Techniques available for cavitation damage repair including: (1) weld overlays and inlays, (2) reinforced epoxy coatings, and (3) thermal spray coatings. Of these methods, the one most commonly used is the weld overlay because it produces the most durable coating. Two weld repair processes generally used for cavitation repair are: (1) gas metal arc welding (GMAW) or metal-inert gas (MIG) welding, and (2) shielded metal arc welding (SMAW) or stick electrode welding (Rodrigue 1986).

Due to the condition of most cavitated surfaces, damage generally cannot be repaired by directly filling the pitted areas. The pitted surface is usually undercut to remove the damaged area and to provide a surface that can be adequately cleaned before filling repair. The resulting space is normally filled by welding with a common stainless steel alloy such as 308L or 309L. The top 0.25 in. layer is usually 308L stainless steel. 309L stainless steel is used when the first pass is on mild steel. 309L has higher Cr and Ni content, and can withstand dilution with the mild steel without a loss of properties for cavitation resistance. However, if the substrate to be repaired is stainless steel, 308L can be used.

Extensive weld repair can introduce stresses in the area being repaired and can damage the component. Entire throat rings have required stainless steel weld repair. Complete welding of the throat ring produces thermal stresses on cooling that cause the weld overlay and liner to pull away from the concrete support. The detached steel liner is subject to buckling and damage. In order to prevent this disbonding and overstressing of the liner, anchors and grout are used.

Thermal Spray Processes

Thermal spraying is a process by which finely divided metallic or nonmetallic materials are deposited in a molten or semimolten condition on a prepared substrate to form a sprayed deposit. Thermal spray processes include combustion powder flame spray, combustion wire flame spray, wire arc spray, plasma spray, and high velocity oxyfuel (HVOF) spray (Figures 2 and 3).

Thermal spraying that uses the heat from a chemical reaction is known as combustion gas spraying, or *flame spraying*. Any material that does not sublime (i.e., does not transform directly from a solid to gas) and has a melting temperature of less than 5000 °F may be flame sprayed. Materials that are applied by flame spray include metals or alloys in the form of wire, cord, or powder; ceramics as powder, cord, or rod; and polymers as powder.

Combustion wire flame spray feedstock material is mechanically drawn by drive rollers into the rear of the gun. The feedstock proceeds through a nozzle where it is melted in a coaxial flame of burning gas. One of the following gases may be combined with oxygen for use in flame spraying: acetylene, methylacetylene-propadiene stabilized (MPS), propane, hydrogen, or natural gas. Acetylene is the gas most widely used because of higher flame temperature. The fuel gas flame is used for melting only—not for propelling or conveying the material. To accomplish spraying, the flame is surrounded with a stream of compressed gas—usually air—to atomize the molten material and to propel it onto the substrate.

The combustion powder flame spray process is similar to the wire process but the powder feedstock is stored in a hopper that can either be integral to the gun or externally connected to the gun. A carrier gas is used to convey the powder into the oxygen fuel gas stream where the powder is melted and carried by the flame onto the substrate.

In the wire arc process, two consumable wire electrodes, which are at first isolated from each other, automatically advance to meet at a point in the atomizing gas stream. An electrical potential difference of 18 to 40 volts, applied across the wires, initiates an arc that melts the tip of the wire electrodes. An atomizing gas, usually compressed air, is directed across the arc zone, shearing off the molten droplets that form the atomized spray.

Plasma spray technology uses a plasma-forming gas (usually either argon or nitrogen) as both the heat source and the propelling agent for the coating. A high-voltage arc (up to 80 kW) is struck between the anode and cathode within a

specially designed spray gun. This energy excites the plasma gas into a state of ionization. The excited gas is forced through a convergent/divergent nozzle. Upon exiting the nozzle, the gas returns to its natural state, liberating extreme heat. Powder spray material is injected in the hot plasma stream, in which it is melted and projected at high velocity onto a prepared substrate. The resulting coatings are generally dense and strongly bonded with high integrity (AWS 1985).

The HVOF process efficiently uses high kinetic energy and controlled heat output to produce dense, very-low-porosity coatings that exhibit high bond strength. The HVOF gun consists of a nozzle to mix the combustion gases, an air-cooled combustion chamber, and an external nozzle (air cap). The process gases enter through several coaxial annular openings. A central flow of powder and carrier gas is surrounded by air, fuel, oxygen, and the remaining process air. This focuses the spray stream and prevents the powder from contacting the gun walls. The oxygen and fuel burn as they enter the rear portion of the combustion chamber. Most of the process air is used to cool the combustion chamber and, in the process, is preheated before entering the air cap. As it enters, the process gas forms a thin boundary layer that minimizes the contact of the flame with the walls of the air cap and helps to reduce the quantity of heat transferred to the air cap. Hot gases with a combustion temperature of up to 6000 °F exit through a converging nozzle with a gas velocity that can approach 4500 ft/sec (Metco 1996).

For the application of polymeric or thermal spray coatings the surface must be cleaned and have a suitable profile that will enhance the coating adhesion. Cleaning procedures are designed to remove specific types of contaminants without changing the physical or chemical properties of the substrate surface. Cleaning can be done with solvents that dissolve the contaminants. A rough profile has a greater surface area, which increases bonding capability. Surfaces can be roughened by machining or grit blasting (Ruzga, Willis, and Kumar 1993).

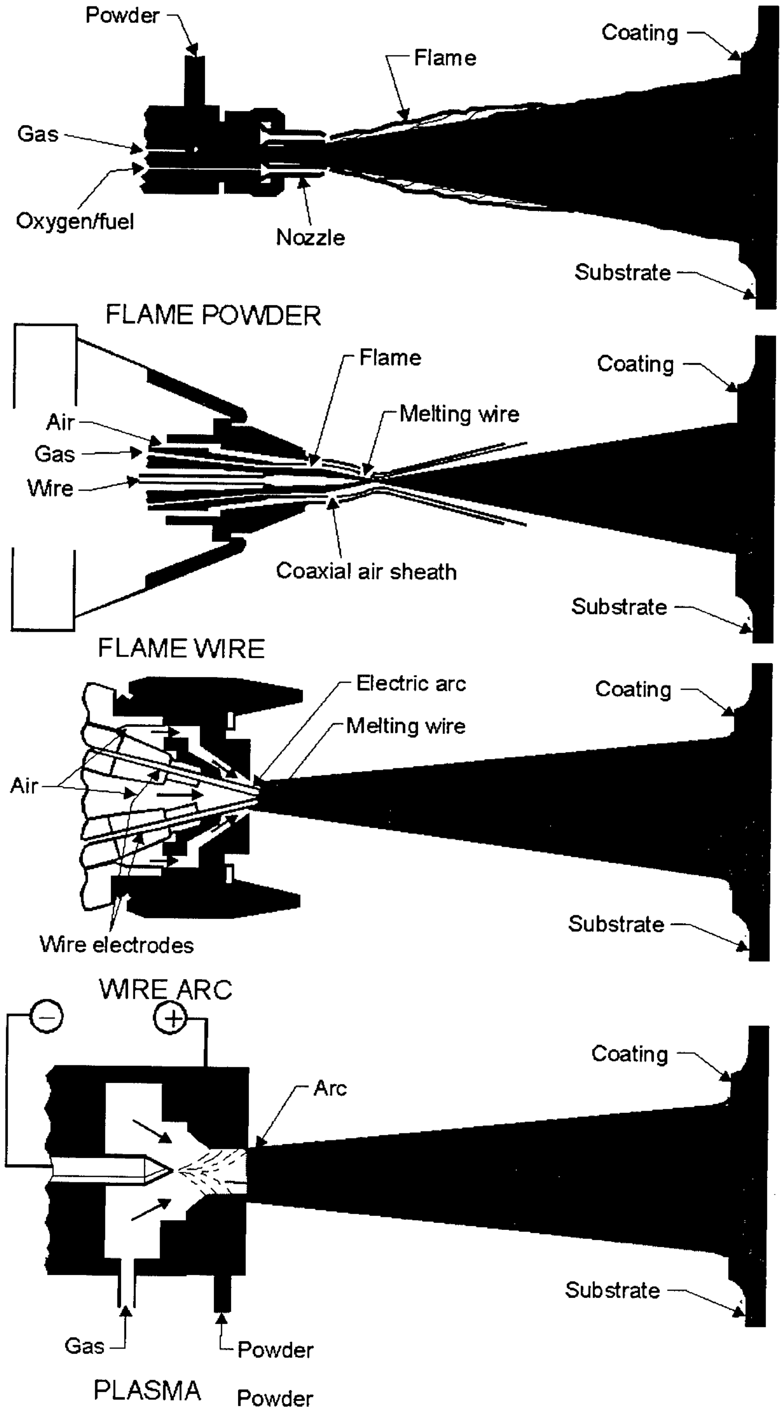


Figure 2. Schematic of various thermal spray processes (Irons 1992).

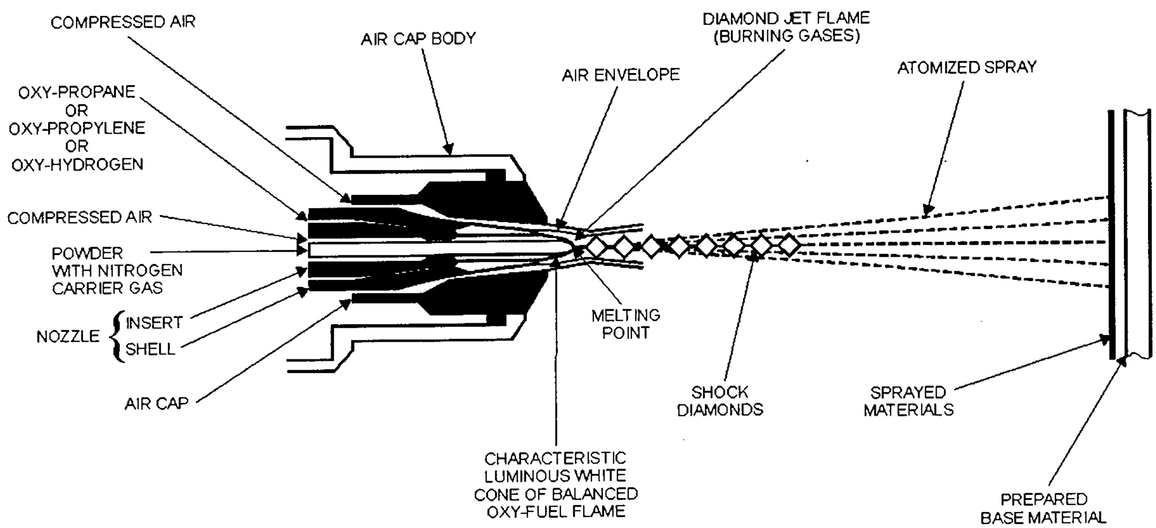


Figure 3. Schematic of High Velocity Oxyfuel (HVOF) thermal spray process (Metco 1996).

Thermal spray coatings are generally limited in the thickness of material that can be deposited. This limit can be as low as 0.030 in. for plasma spray and HVOF coating processes (Irons 1992). However, in some cases 1 in. thick coatings have been applied (Musil, Dolhof, and Dvoracek 1996). Due to thickness limitations, deep cavitation damage would have to be repaired by welding, but thermal spray coatings could be applied to the welded surface to provide additional protection to the component. Thermal spray coatings could also be applied directly to properly cleaned and roughened surfaces that do not require weld repair.

It is anticipated that once a sprayed coating is applied, this coating will prevent damage to the underlying base metal. Because the sprayed coating becomes the active surface, future repairs of the affected area can be made using thermal spray coatings deposited by the HVOF process rather than by weld repair of the substrate, which costs approximately three times as much as flame spraying.

3 Materials for Cavitation Repair

Stainless steels are the most commonly used materials for cavitation repair. The cavitation rates of selected materials, measured in accordance with ASTM G 32 vibratory cavitation test, are shown in Table 1. These rates should be used as an indication of relative—not absolute—wear rates. Several materials, such as cobalt and nickel-based Stellite® alloys and advanced iron based alloys such as Ireca, have superior cavitation resistance compared to stainless steel (Simoneau 1987, 1991). The detailed compositions of these and other materials are shown in Tables 2 and 3. Some of these alloys are now also available in powder form suitable for application by HVOF or plasma spray processes.

Table 1. Cavitation rate of materials using the vibratory cavitation test.

Material	Cavitation Rate (mg/h)
A-27 - Cast	35.0
CA6NM - Cast	15.0
308 Stainless Steel - Welded	15.0
301 Stainless steel - Welded	6.0
Stellite® 21 - Welded	1.4
Stellite® 6 - Welded	0.7
Ireca - Cast	1.0

Source: Simoneau 1991.

The highly cavitation-resistant Ireca steel weld alloy, which was developed by Hydro Quebec and was marketed as Hydroloy® 913 by Stoody Corporation in the early 1990s, has been used with success on cavitation-prone areas of hydro-electric turbine runners. However, the alloy was difficult to weld and grind and is no longer marketed by Stoody. Hydro-Quebec's Ireca steel, following further research and alterations, is now marketed by Castolin Eutectic Corporation under the brand name CaviTec®[1] (Fulton 1996).

[1] Castolin Eutectic Corp., Charlotte, NC

Table 2. Alloy composition (weight percent).

	Co	Cr	Mo	Ni	Mn	Fe	Si	C	W
Tribaloy® T-400[2]	Bal.	8.50	28.5	1.5		1.5	2.6	<0.08	-
Tribaloy® T-700[1]	1.50	15.5	32.5	Bal.		1.5	3.4	<0.08	-
Tribaloy® T-800[1]	Bal.	17.5	28.5	1.50		1.5	3.4	<0.08	-
Stellite® 6[1]	Bal.	28	3	3		3	1.1		4
SAE 1020					0.2	Bal.	0.2	0.2	
430 Stainless Steel**		14-18	1.0	<0.5		Bal.	<1.0	<0.12	
431 Stainless Steel**		15-17	1.0	1.25-2.5		Bal.	<1.0		-
308 Stainless Steel*		20	2.0	8.9		Bal.	0.83	0.04	-
309 Stainless Steel**		22-24	2.0	12-15			<1.0		
316 L		17	2.5	13		Bal.	1	0.03	-
Metco 71 VF-NS-1[3]	12	-	-	-		1	-	4	Bal.
Nistelle® C[1]	2.50	16.50	17.00	Bal.		5.75	1.0	0.12	4.5
Nistelle® D[1]	1.50	0.75	-	Bal.		2.0	9.25	0.12	-
	Co	**WC**							
Sylvania Osram 150A	17	83							
	B	**Cr**	**Mo**	**Ni**		**Fe**	**Si**	**C**	**Cu**
NiCrBSi Alloy	4.0	16.0	3.0	Bal.		2.5	4.0	0.05	3.0
	Zr	**Al**		**Ni**					
85-15 Zn-Al	85	15							
Ni - 5 Al		5		95					

* Simoneau 1991.

** Typical composition (Fontana and Green 1987).

Other advanced iron-based cavitation-resistant alloys that have recently entered the market include Hydroloy® 914, marketed by Stoody Corporation; NOREM®[4], developed by the Electric Power Research Institute (EPRI); and D-CAV®[5], marketed by Demand Arc, Inc. (Table 3). Compared to Hydroloy 913, Hydroloy® 914 contains higher silicon content (up to 5 percent) along with an increase in nickel to 2 percent (Menon, Moiser, and Wu, 1996). Hydroloy® 914 is presently available only as weld wire and not in powder form for thermal spraying.

NOREM® is a cobalt-free iron-based alloy originally developed for the nuclear industry, but has applications in the hydroelectric area as well. An advantage of

[2] Stoody Deloro Stellite, Inc., Goshen, IN

[3] Sulzer Metco, Inc., Westburry, NY

[4] EPRI, Palo Alto, CA

[5] Demand Arc, Inc., Chattanooga, TN

NOREM® and D-CAV® is the lower cost compared to cobalt-based alloys. NOREM® is available in both wire and powder forms. D-CAV® is a proprietary austenitic stainless steel and is available only in wire form. Although some of these advanced materials are not currently available in powder form suitable for thermal spray application, their reported excellent cavitation resistance warranted inclusion in the test matrix. It is hoped that these alloys will be available in the future in powder form.

Table 3. Composition of advanced iron-based alloys (weight percent).

	Fe	C	Mn	Si	Cr	Ni	Co	N	Mo	P	S
308 Stainless*	Bal.	0.04	1.7	0.83	20	8.9		0.05			
Ireca*	Bal.	0.3	10	3	17	-	10	0.1			
Hydroloy® 913*	Bal.	0.2	10	3	17	-	10	0.2			
Hydroloy® 914**	Bal.	0.22	10	4.6	17	2.0	10	0.3			
NOREM® Powder***	Bal.	1.17	12.2	5.1	25.3	8.2		0.22	1.8	0.03	0.01
NOREM® Wire***	Bal.	1.19	6.0	4.1	25.3	4.6		0.11	1.2	0.008	0.006
CaviTec®	Proprietary austenitic stainless steel										
D-CAV®	Proprietary austenitic stainless steel, cobalt free										

* Simoneau 1991.

** Menon, Moiser, and Wu 1996.

*** Orkin 1995.

4 Cavitation Testing Methods and Previous Research

Laboratory Techniques

There are three principal laboratory testing techniques to determine cavitation rates:

- ultrasonic cavitation testing
- cavitating jet testing
- venturi cavitation testing.

The cavitation rate is usually given in terms of weight loss per time period. However, the rate can also be reported in terms of a change in thickness per time period or a volume loss per time period.

Ultrasonic Method

The ultrasonic (vibratory) method of cavitation testing uses a magnetostrictive or piezoelectric device to produce a high-frequency (generally 20 kHz) vibration in a test specimen immersed in a liquid (Figure 4). During one half of each vibration cycle, a low pressure is created at the test specimen surface, producing cavitation bubbles. During the other half of the cycle, bubbles collapse at the specimen surface. It is a simple, relatively fast, and inexpensive technique and has been the most widely used technique for cavitation testing (March and Hubble 1996). A standard test procedure for ultrasonic cavitation testing has been approved by the American Society for Testing and Materials (ASTM) as Standard G 32 (ASTM 1992). The technique has been modified by placing the test specimen a small distance below the tip of the ultrasonic probe (Schwetzke and Kreye 1996).

Results of ultrasonic vibratory cavitation testing for polymer coatings on concrete were reported to not correlate well to the field cavitating conditions. The ultrasonic test apparatus was not able to reproduce in the laboratory the same type adhesion failures that frequently occurred for polymer coatings under field conditions (Cheng, Webster, and Young 1987).

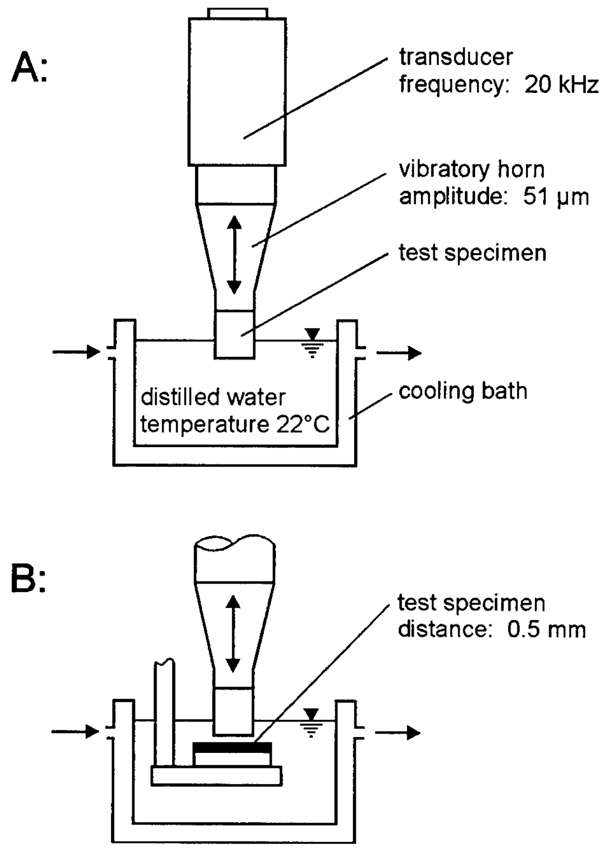


Figure 4. Ultrasonic cavitation testing: (A) ASTM G 32 (B) Modified method (Schwetzke and Kreye 1996).

Cavitating Jet Method

The cavitating jet method for cavitation testing uses a submerged cavitating jet to erode a test specimen placed in the jet's path (Figure 5). This technique is relatively compact and provides a higher range of cavitation intensities than do the ultrasonic probe method or the venturi method.

The cavitating jet test methodology was found to provide consistent, reproducible results for a given operating condition. The relative cavitation rate, referenced to a standard material, provides a good method for comparing materials that have a wide range of properties (March and Hubble 1996).

The TVA has used the results obtained from laboratory cavitating jet testing to select weld materials for field demonstrations. Weld materials that had higher cavitation resistance compared to welded stainless steel in the laboratory also performed better than stainless steel in the field (Karr et al. 1990). The cavitating jet laboratory test results for weld alloys were found to correlate well with field experience.

Therefore, based on results reported in the literature, the cavitating jet test is better than the ultrasonic cavitation test at predicting the field performance of materials.

Venturi Cavitation Method

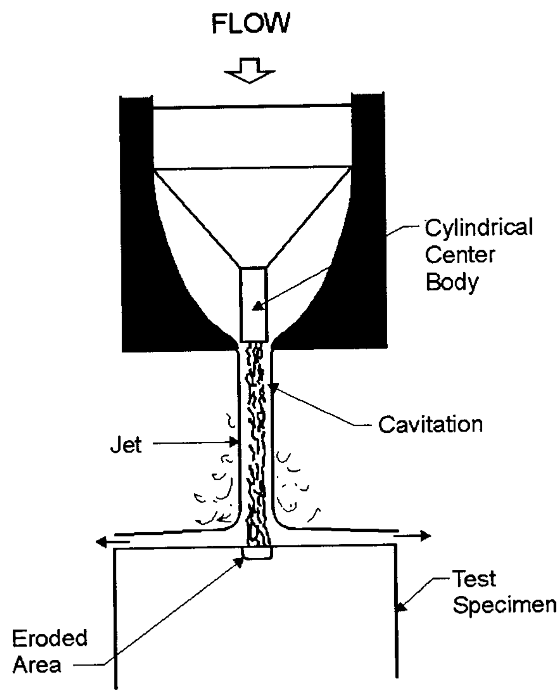


Figure 5. Schematic of Cavitating Jet testing apparatus (March and Hubble 1996).

A venturi-type cavitation testing machine is shown in Figure 6. An uncoated steel test panel served as the control specimen. The inlet pressure was maintained at approximately 60 psi, producing a water velocity of approximately 70 ft/sec through the venturi throat. This generated a sustained, moderately cavitating environment. This test required that the panels be removed on a regular basis from the test apparatus, inspected, weighed, and returned to the test apparatus until failure was observed (Baker 1994). The venturi cavitation method was found to require long times to complete the test—as many as 2078 hours—so it was deemed inappropriate for this research.

Results of Lontz 1992

Cavitation barrier coatings were applied in June 1989 to the backside of one blade of a Kaplan Turbine Unit at Rocky Reach Dam, Unit #13, Chelan County Public Utility District (PUD), Washington. Approximately 45 sq ft along the outer edge of the blade was coated with Tribaloy® T-400 and an urethane top coat.

Chelan County Public Utility District (PUD) personnel repaired all the previous cavitation damage, restoring the blade's shape and contour. Chelan County PUD personnel, assisted by a contractor, grit blasted the surface to be coated. The contractor set up the cavitation barrier equipment and applied Tribaloy® T-

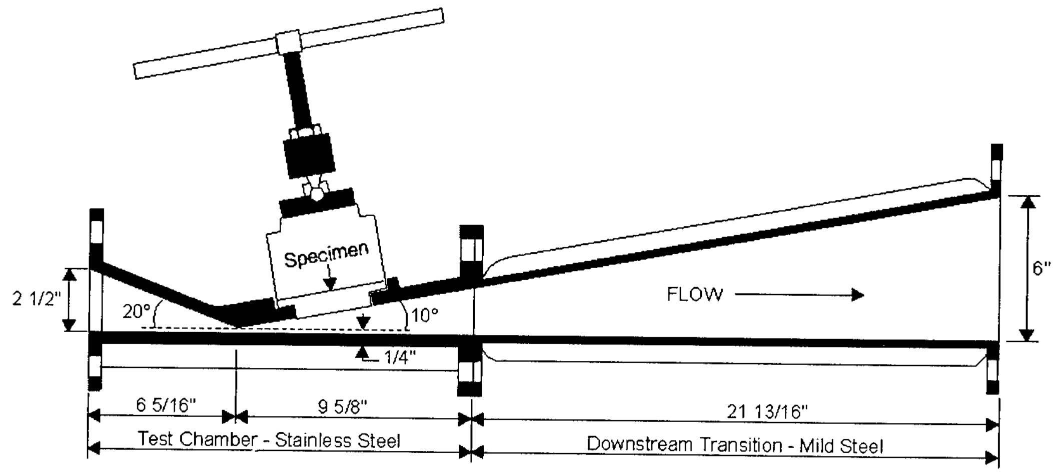


Figure 6. Venturi cavitation testing apparatus (Baker 1994).

400 coating using HVOF equipment. A urethane coating was brush-applied over the Tribaloy coating.

Two problems were encountered with the application of the cavitation barrier coatings:

1. High-velocity equipment was not designed to be taken into turbines, so there were problems with fuel gases, degassing and powder feed.

2. When the first coating of Tribaloy was applied several problem areas were noted and the entire coating was found unsatisfactory. The coating was removed and a new coating applied.

Based on further experience in the field, these problems can be overcome by implementing a number of changes to the procedure:

1. The proper attention to preparation of the surface is required. In the case of turbine blades, grit blast the area to be coated one day before the application of the coating, followed by the use of heat blankets on the top of the blades for approximately 12 hours to remove moisture from the surface and prevent condensation. Grit blast the surface to be coated to white metal finish just before spraying. After application of the Tribaloy coating, the urethane coating would be sprayed (rather than brush-applied) to improve thickness and finish.

2. Fuel bottle heaters are now available to help maintain fuel temperature in a cool environment. Insulating the fuel lines will also help maintain the fuel gasses.

3. The Metco Diamond Jet HVOF equipment has since been modified to address powder feed problems.

Inspection in June 1990 found approximately 15 sq ft of cavitation barrier coating in basic contact on the bottom portion of the blade although the urethane coating had come off in large pieces. The HVOF Tribaloy® T-400 coating appeared intact in an area of mid-blade. However, the areas of the blade most vulnerable to high cavitation had no remaining cavitation barrier coating. (This area is the outer tip of the blade, approximately 4 x 8 ft). Some minor cavitation damage to the underlying metal was noted—approximately 8 x 3 in.—with a waviness of the blade surface in the area of the cavitation.

It was concluded that the Tribaloy® T-400 applied by HVOF and coated with urethane had an impeding effect on the cavitation. Improvements in equipment, technique, and experience levels would be expected to provide better results (Lontz 1992).

Results of Baker 1994

The Bureau of Reclamation conducted a study for USACERL to determine the cavitation resistance of inorganic and ceramic coatings applied over steel substrates. Testing was conducted in a Venturi-type cavitation testing machine (see Figure 6). An uncoated steel test panel served as the control specimen. The inlet pressure was maintained at approximately 60 psi producing a water velocity through the throat of approximately 70 ft/sec. This generated a sustained, moderately cavitating environment. A criterion for coating failure was established for coated panels as the time when 1 to 2 percent or more of the coating had been removed down to the substrate. The test panels were inspected at regular intervals to determine time of failure (Baker 1994).

Two sets of cavitation results are presented in Table 4. The first set contained a mild steel control sample and two coated samples: Panel 11, metallized coating (Stellite Tribaloy® T-400) and an organic topcoat (total 50 mils); Panel 12, 24 mils Stellite Tribaloy® T-400 and 10 mils organic topcoat of a reinforced epoxy

(Belzona Superglide®[1]). Belzona Superglide® is a two-component nonmachinable-grade material consisting of a silicon steel alloy blended within high molecular weight reactive polymers and oligomers.

The second set of results consisted of three sets of samples: Panel 21, stainless steel; Panel 22, stainless steel plus 10 mil Stellite Tribaloy® T-400 applied by wire feed thermal spray; and Panel 23, stainless steel plus 10 mil Stellite Tribaloy® T-400 + 20 mil organic topcoat of a reinforced epoxy (Belzona Superglide®).

The metallized coatings were ranked according to time to first damage. The best performer, with a time to first damage of 565 h, was Panel 12: 24 mils Tribaloy® T-400 + 10 mils of a reinforced epoxy (Belzona Superglide®). Second best, with a time to first damage of 386 h, was Panel 23: 10 mils Tribaloy® T-400 and 20 mils of a reinforced epoxy (Belzona Superglide®). Third best, with a time to first damage of 218 h, was Panel 11: metallized coating (Tribaloy® T-400) and organic topcoat (total 50 mils). The fourth best, with a time to first damage of 186 h, was Panel 22: 10 mils Tribaloy® T-400. The organic topcoat, a reinforced epoxy (Belzona Superglide®), was found to extend the life of the metallized coating (Tribaloy® T-400). Although the topcoat was found to fail early, it did provide added protection when present. The reinforced epoxy (Belzona Superglide®) topcoats were found to be superior to polyurethane topcoats (Baker 1994).

The results of Baker showed that the time to failure of stainless steel was 2075 hours, the time to failure of mild steel was 1038 hours, and the time to failure of the metallized Tribaloy® T-400 was 545 hours. The time to failure during cavitation testing of the metallized Tribaloy® T-400 coating was found to be less than either the carbon steel or the stainless steel.

Problems encountered during the testing included:

1. Water flow across the panels was not uniform.

2. The depth of the testing surface in the cavitating water stream was inconsistent. Samples of mild steel showed that panels placed deeper in the water stream sustained more severe cavitation damage than the control panel.

[1] Belzona Inc., Miami, FL

3. Long exposure times were required to complete the test—as long as 2078 hours, limiting the number of samples that may be tested in a reasonable period.

The results obtained using the Venturi cavitation testing apparatus provided valid insights into the material systems tested, but the long testing periods required made the technique inappropriate for this CPAR research.

Table 4. Cavitation resistant properties of coating systems tested on a venturi-type cavitation testing machine (Baker 1994).

Sample	Coating System	Total Coating Thickness over Stainless Steel (mils)	Time Until First Damage (hours)	Time Until First Damage (hours)	Time Until First Damage (hours)	Time Until Failure (hours)	Total Loss of Materials (grams)	Total loss of Material as Determined from % Bare Area	Total Average loss of Thickness (mils)	Percent Loss of Coating Thickness	Comments
			Organic Coating	Metallized Coating	Uncoated Panel						
11 Interim Report	Organic Topcoat - Polyurethane (10 mils) 20% Cr, 35% Ni & 45% Fe (38 mils)		11	142	-------	218	38	30-35%	19	38%	
12 Interim Report	Organic Topcoat - Polyurethane (10 mils) 29.5% Mo, 8.5% Cr & 57% Co (Tribaloy® T-400) (24 mils)	34	9	538	-----	565	11	10-15%	13	38%	Baker's Conclusion: "Best performance of metallized coatings. Organic topcoat began to fail very early in the test."
Uncoated Steel Interim Report		Uncoated Mild Steel	-----	-----	200	1,115	4	Uncoated Mild Steel	3	Uncoated Mild Steel	
Uncoated Steel Final Report	(0.30 mils thicker samples. Introduced sample height as test variable)	Uncoated Mild Steel	-----	-----	752	1,038	16	Uncoated Mild Steel	7	Uncoated Mild Steel	Baker's Conclusions: "Depth of testing surface effected the severity of the test. Data showed an appreciable increase in damage when testing surface was immersed deeper in the cavitating water stream."
21 Final Report	308 S. Steel Topcoat (1/8 in) 309 S. Steel Welded (1/8 in.) mild steel base	Uncoated Stainless Steel	-----	-----	347	2,075	8 Apparent	Uncoated Stainless Steel	5	Uncoated Stainless Steel	Apparent weight loss reported: Sample was damaged during testing due to loosening in test rig. Actual weight loss from pure cavitation was less.
22 Final Report	Tribaloy T-400 (10 mils) 308 S. Steel Topcoat (1/8 in.) 309 S. Steel Welded (1/8 in.) mild steel base	10	------	154	-----	186	5	15-20%	4	40%	Baker's Conclusion: "Metallized (ceramic) coatings show more promise as cavitation resistant materials than organic coatings systems."
23 Final Report	Belzona Superglide® 2 coats (20 mil = 0.508 mm total) Tribaloy® T-400 (10 mils) 308 S. Steel Topcoat (1/8 in) 309 S. Steel Welded (1/8 in) mild steel base	30	9	361	-----	386	16	10-15%	14	46%	Baker's Conclusion: "Distinct evidence that some organic topcoats applied over metallized coatings extend the life of the total system."

Results of Soares, Souza, Dalledon, Baurque, and Amado 1994

Tests were performed on thermal spray coatings with both liquid impingement and vibratory cavitation devices. Some of the best coatings were tested further in a 6 meter Francis hydroelectric turbine with a previous history of severe cavitation. The materials investigated and the erosion and cavitation resistance results are shown in Table 5. The cavitation rate was given as a change in thickness of the coating (μm/h).

Table 5. Results of erosion and cavitation resistance tests (Soares et al. 1994).

No.	Designation	Description	Hardness	Method of Application	Thickness (mm)	Relative Erosion Rate ASTM G 73	Cavitation Rate ASTM G 32 (μm/h)	Field Test
	SAE 1020	Fe, 0.2C, 0.5 Mn, 0.2 Si	Rb 80	Substrate		1.0 X	7.5	
	AWS 309	Fe 23 Cr, 13 Ni, 2.7 Mo	Rb 92	Weld			3.9	
1	Diamalloy 1003	Stainless steel, aust., Fe-Cr-Ni	Rb 89	HVOF	1.2-1.7	1.3 X		Field Tested
2	Diamalloy 1005	Ni-Cr-Mo	Rc 30-34	HVOF	1.0-1.7	0.8 X		Field Tested
3	Diamalloy 2001	Ni + Cr alloy, fusible	Rc 53-58	HVOF	1.2-1.7	1.7 X		
4	Diamalloy 2003	WC + 12 Co	Rc 64-65	HVOF	0.15-0.25	Failed		
5	Diamalloy 3001	Co + Cr, Mo Alloy	Rc 50-55	HVOF	0.4-0.6	Failed		
6	Diamalloy 4006	Ni Alloy	Rc 38	HVOF				Field Tested
7	Metco 72 NS	WC + 12 Co	Rc 50-55	Plasma	0.5-0.8	Failed		
8	Metco 101 NS	94 Al_2O_3, 2.5 TiO_2, 2 SiO_2	Rc 55	Plasma	0.7	Failed		
9	Metco 443	Ni-Cr/Al	Rb 90	Plasma	0.5	2.0 X	11	
10	Metco 601 NS	60 Al, Si + polyester	R 15y 73	Plasma	1.4	Failed		
11	Metco 505	Mo alloy	Rc 40-45	Plasma	0.5		65	
12	Metco 81 NS	75 Cr_2O_3 + 20 NiCr	Rc 37-39	Plasma	0.4		100	
13	Chersteron Abrasion Putty	Epoxy + particles of ceramic and Al silicate	Shore D 88	Spatula	2.0		630	
14	Devcon Carb. A	Epoxy + SiC (Coarse)	Shore D 85	Spatula	3.0			Field Tested
15	Devcon Paste	Epoxy + SiC (Fine)	Shore D 85	Spatula	2.0			Field Tested

Coatings number 1 – 5 and 7 – 10 were tested in a liquid impingement erosion test apparatus in accordance with ASTM Standard G 73. The erosion resistance of samples 1, 2, 3, and 9 were of a similar order of magnitude as the SAE 1020 steel reference material. Samples 4, 5, 7, and 8 failed the test as the coating came off the substrate. The cavitation resistance of coated samples, measured using a vibratory testing apparatus in accordance with modified ASTM Standard G 32, was generally lower than the carbon steel reference material. The

cavitation resistance of the ceramic-loaded polymer, sample 13, was significantly lower than for the thermal sprayed metal or ceramic coatings.

Thermal spray and polymeric coatings were applied in a turbine at the Gov. Bento Munhoz hydroelectric project of COPAL (Companhia Paranaense de Energia, or Energy Company of Parana [Brazil]). Coatings number 1, 2, and 6 were applied over stainless steel weld layers in areas of medium cavitation. Polymer coatings number 14 and 15 were applied in areas of low to medium cavitation in the same turbine. After 1500 hours of operations it was observed that coatings 1, 2, and 6 were gone to various degrees, with there being more area of coating 6 and less area of coating 1 gone. The polymeric coatings 14 and 15 were completely gone in areas where the substrate was stainless steel, but in the area of carbon steel the coatings were relatively well retained. In these protected areas the intensities of cavitation were lower. During the same time of operation, the carbon steel regions without coatings, subjected to low or medium cavitation, did not show any indication of cavitation.

Soares et al. (1994) concluded that despite their elevated hardness and/or abrasion resistance, the best thermal sprayed coatings were at best only similar to carbon steel (SAE 1020 or AWS 309 stainless steel) based on the cavitation resistance as evaluated in the laboratory tests. Additionally, since these coatings can be applied only to a very small thickness (i.e., 0.5 mm), they found little or no advantage compared to conventional welded layers for turbine blades. An additional problem of poor adhesion was observed during the field tests in the hydroelectric turbine: the sprayed layers simply peeled off after a few months of operation (Soares et al. 1994). Based on laboratory and field data the researchers concluded that thermal spray coatings were not suitable in severe cavitation applications.

Results of March and Hubble, 1996

Cavitation testing of mostly weld materials and some other coating materials was conducted at the Tennessee Valley Authority (March and Hubble 1996). The cavitating jet test apparatus was used at 4000 psi (Table 6). Weld overlay material including Ireca, Nitronic 60, Stellite® 6, Stellite® 21, Stoody 6, and Stoody 2110 with one coating Imperial Clevite WC-204 were found to have substantially lower cavitation rates than the 308 stainless steel reference panel. The cobalt-containing austenitic stainless steel, Ireca, had a relative cavitation rate of 0.02 times that of 308 stainless steel—the lowest rate among all the materials tested.

In addition to weld alloys, this work included testing of thermal spray coatings such as Hardco spray 110, Hardco spray Stellite 21, Plasmadynne plasma spray Stellite 21, and several elastomeric materials including Devcon pump repair epoxy, Belzona ceramic reinforced epoxy, and a nylon coating. In general, the coatings displayed higher relative cavitation rates compared to 308 stainless steel, with rate values ranging from 11 to 67 times that of the reference panel. However, the relative cavitation rate of one coating—Imperial Clevite WC-204—was 0.3 times that of the reference. Coatings were also susceptible to mechanical damage and bond failure under the test conditions (March and Hubble 1996).

Table 6. Cavitation rates using cavitating jet test apparatus at 4000 psi.

Material	Cavitation Rate (mg/h)	Relative Cavitation Rate vs 308 Weld	Ranking
Ireca Weld	0.2	0.02	1
Stellite® 21	0.9	0.1	2
Stoody-6	2.1 Surface cracking	0.2	3
Stellite® 6 Weld	2.2 Surface cracking	0.2	4
Imperial Clevite WC-204	2.5	0.3	5
Armco Nitronic 60	2.5	0.3	6
Armco Nitronic 60 Weld	2.9	0.3	7
Stoody 2110 weld	3.2	0.3	8
Hardco 110 Weld (Cr-Mn steel)	3.7	0.4	9
304 Stainless Steel	7.0	0.7	10
Eutectic 646XHD	7.1	0.7	11
316 Stainless Steel	7.6	0.8	12
309 Stainless Steel Weld	9.1	0.9	13
308 Stainless Steel Weld	9.8	1.0	14
Eutectic Eutectrod 40	10.2	1.0	15
316 Stainless Steel Weld	13.4	1.4	16
347 Stainless Steel Weld	13.7	1.4	17
Carbon Steel	15.9	1.6	18
E7018 weld	16.5	1.7	20
Al - Bronze Weld	36.0	3.7	19
Plasmadyne Plasma Spray Stellite 21	105.6	10.8	21
Metco PFX-5000	114.00	11.6	22
Devcon pump repair epoxy	190.0	19.4	23
Belzona® Ceramic EC over Ceramic R	274.0	28.0	24
Hardco flame spray 110	660.0	67.3	25
Devcon WR2	792.0	80.08	26
Wear Cont. Tech Nylon II	Surface delamination	----	27
Hardco Spray Stellite 21	Surface delamination	---	28
S.S. Urethane Techthane 80 SS	Surface puncture	---	2829

Source: March and Hubble 1996.

Based on the results of March and Hubble (1996), advanced weld alloys such as Ireca alloys (marketed as Hydroloy® 913) provided superior cavitation resistance and were recommended for use in areas of severe cavitation. TVA in 1988 successfully tested Hydroloy® 913 (the commercial form of the Ireca alloy) on the runner and crown of a hydroelectric pump/turbine at Raccoon Mountain, Chattanooga, TN. Following inspection in 1990, after 6782 hours of operation, the turbines blades repaired with Hydroloy® 913 had significantly less cavitation damage than blades repaired with 309L stainless steel (Karr et al. 1990).

Results of Schwetzke and Kreye, 1996

Cavitation experiments were performed using a vibratory apparatus according to ASTM G 32, modified to place the test specimen 0.5 mm below the vibrating steel disc of the ultrasonic horn. Tests were conducted for up to 5 hours. The steady-state cavitation rates of the coatings tested are given in Table 7. For the cermet (metal ceramic alloy) and oxide coatings tested, the mass loss versus exposure time revealed an almost constant erosion rate between 1 and 5 hours of testing.

Coatings investigated included stainless steel (316L), self-fluxing nickel-based alloys (NiCrFeBSi, type 60), tungsten carbide-cobalt (WC-17 Co), chromium carbide-nichrome (Cr_3C_2-25 NiCr), and chromium oxide (Cr_2O_3). The results demonstrated that HVOF-sprayed coatings of NiCrFeBSi, WC-17 Co, Cr_3C_2-25 NiCr, and Cr_2O_3 exhibited erosion rates as low as that obtained from bulk specimens of stainless steel (AISI 321 or 316 L). However, the cavitation rates of plasma sprayed cermet coatings were about an order of magnitude higher than the erosion rate of the best HVOF coatings (Schwetzke and Kreye 1996). A similar high difference of the erosion rates of plasma sprayed as compared to HVOF-sprayed cermet coatings has recently been reported for the removal of those coatings by high-pressure water jets (Kreye et al. 1995).

HVOF coatings of NiCrFeBSi, WC-17Co, Cr_3C_2-25 NiCr and Cr_2O_3 exhibited rather high resistance to cavitation and were recommended for consideration as a protective surface layer against cavitation (Schwetzke and Kreye 1996). This study provides support for the use of these materials in the repair of hydroelectric turbine components such as draft tube liners.

Table 7. Cavitation rate of thermal sprayed coatings.

Spray Process	System	Fuel	Material	Hardness (VHN 300 g)	Cavitation Rate (mg/h)
HVOF	JP-5000	Kerosene	Stainless Steel 316 L	263	6.8
HVOF	Jet Kote	Propane	NiCrFeBSi type 60	674	4.3
HVOF	JP-5000	Kerosene	NiCrFeBSi type 60	767	4.7
HVOF	Top Gun	Hydrogen	Tribaloy® T-400	579	20.4
HVOF	Top Gun	Hydrogen	Tribaloy® T-700	589	12.4
Plasma	A-3000 S	Ar / H_2	WC-Co 88-12	764	74.8
HVOF	Top Gun	Propane	WC-Co 88-12	1178	11.9
HVOF	Top Gun	Propane	WC-Co 83-17	1376	5.8
HVOF	Jet Kote	Propane	WC-Co 83-17	1052	30.0
HVOF	Jet Kote	Propane	WC-Co 83-17	1127	23.4
HVOF	Jet Kote	Ethylene	WC-Co 83-17	1243	22.8
HVOF	DJ 2700	Ethylene	WC-Co 83-17	1399	7.2
HVOF	JP-5000	Kerosene	WC-Co 83-17	1420	6.3
Plasma	A-3000 S	Ar / H_2	Cr_3C_2-NiCr 75-25	722	59.5
HVOF	Top Gun	Propane	Cr_3C_2-NiCr 75-25	1021	17.6
HVOF	Jet Kote	Propane	Cr_3C_2-NiCr 75-25	978	13.9
HVOF	DJ 2700	Ethylene	Cr_3C_2-NiCr 75-25	1134	5.5
HVOF	JP-5000	Kerosene	Cr_3C_2-NiCr 75-25	1220	3.8
Plasma	A-3000 S	Ar / H_2	Al_2O_3-TiO_2 97-3	772	52.8
HVOF	Top Gun	Acetylene	Al_2O_3-TiO_2 87-13	972	24.7
Plasma	A-3000 S	Ar / H_2	Cr_2O_3	1322	6.6
HVOF	Top Gun	Acetylene	Cr_2O_3	1210	2.9
Bulk material:	Stainless Steel X6 CrNiTi 18 10 (type 321)			226	5.5
Bulk material:	Stainless Steel X2 CrNiMo 17 13 2 (type 316 L)			165	6.0

Source: Schwetzke and Kreye 1996.

Results of Musil, Dolhof, and Dvoracek 1996

The wire arc spray (WAS) process of functional and multilayered coatings was successfully used for the repair of vanes on reversible Francis turbines (Musil, Dolhof, and Dvoracek 1996). The two-wire arc spray process employs the spraying of two different wire materials to create a mixed or graded coating structure. NiAl and Cr stainless steel were used for the two-wire arc spraying. NiAl (95% Ni - 5% Al) is widely used in the power industry. Wire sprayed NiAl coatings have shown higher bond strengths than plasma sprayed coatings and also maintain their high bond strength at greater thicknesses (Unger and Grossklaus 1992). High-chromium stainless steel was selected as the spray material for the functional top-coat. Due to the severe cavitation damage, with some pit depths greater than 25 mm, the deposition of very thick coatings was

required. Damaged materials were removed and the surface cleaned and grit blasted before application of the repair coating.

Thick multilayered coatings deposited by WAS were evaluated for the repair of vanes on a Francis turbine. Three types of functional graded coating were evaluated: (A) a duplex of high Cr stainless steel with NiAl bond coat, (B) bond coat, graded NiAl -Cr stainless steel coatings with a Cr stainless steel top coat, and (C) multilayered graded NiAl-Cr stainless steel coatings with a Cr stainless steel topcoat (Figure 7). The alternating layers in the NiAl-Cr stainless steel multicomponent graded coating were approximately 1.5 mm thick. Laboratory analysis showed that the multilayered graded NiAl-Cr stainless steel coatings (Figure 7C) yielded the best results with the lowest residual stress.

Repair was performed on large eroded areas (1-3 m^2) of the vanes on a Francis turbine. Localized cavitation damage with pit depth of 30–35 mm maximum was repaired by sprayed materials. Multilayered graded NiAl-Cr stainless steel coatings (Figure 7C) were applied by the WAS process to stationary wicket gate supports in four hydroelectric power stations located in the Czech Republic. The main steps in the repair process were:

- examination
- alumina blasting
- hand working with power tools and chemical cleaning
- alumina blasting
- local WAS application of extremely damaged parts

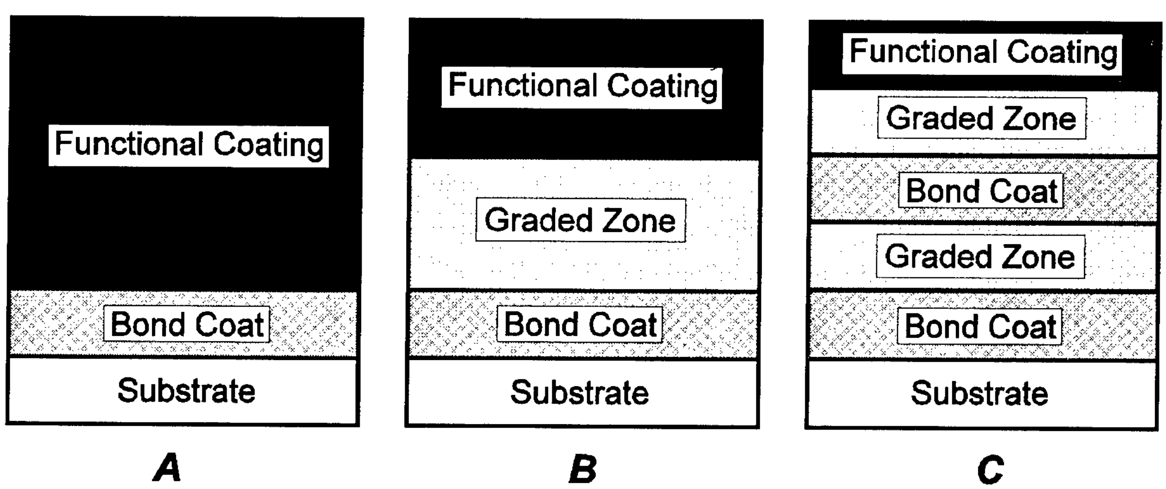


Figure 7. WAS coatings (A) Duplex of high Cr stainless steel with NiAl bond coat, (B) Bond coat, graded NiAl -Cr stainless steel coatings, and Cr Stainless steel, (C) Multilayered bond and graded NiAl-Cr stainless steel coatings and Cr stainless steel topcoat. Source: Musil, Dolhof, and Dvoracek 1996.

- hand working with power tools and blasting
- WAS application of functional multilayered graded coatings
- application of special seals
- hand working with power tools and special seal application.

The seal material was not specified. After 30–36 months of continuous operation, the coatings applied by WAS showed better performance in comparison to the original carbon steel (Musil, Dolhof, and Dvoracek 1996). This demonstrated the successful use of thermal spray coatings for the repair of hydroelectric components and provides additional support for their use. However, for severe cavitation damage, the authors of the current study recommend weld repair. As will be shown, advanced iron-based weld alloys such as D-CAV®, NOREM®, CaviTec®, or Hydroloy® 914, may be considered for the repair of severe cavitation damage.

5 Experimental Procedures

Material Selection

Based on the results from the literature reviewed in Chapter 4, materials were selected for further evaluation and testing as thermal sprayed coatings applied either by HVOF or plasma spray processes. This includes the results that showed Tribaloy® T-400 applied by HVOF had an impeding effect on the cavitation of substrate (Lontz 1992; Baker 1994). Therefore, other similar hardfacing alloys were also selected.

Based on findings from the literature reviewed, a list of cavitation repair materials that can be thermally sprayed by high-velocity and plasma processes was prepared by SUNY. These included hard facing alloys based on cobalt (Stellite® 6, Tribaloy® T- 400 and Tribaloy® T-800) and tungsten-carbide-based alloys (Metco 71 VF-NS-1 and Sylvania Osram 150 A).

Bulk and welded cobalt-based Stellite® 6 have lower cavitation rates compared to 308 stainless steel, as shown previously in Tables 1 and 3 (Simoneau 1991; March and Hubble 1996). Other cobalt-based hard facing alloys include Tribaloy® T-400 and Tribaloy® T-800, which contain 8–17% Cr and 28% Mo, in contrast to the Stellite® 6, which has 28% Cr and 3% Mo (see Table 2). The characteristic high hardness and wear resistance of thermal sprayed WC - Co materials have made them the material of choice for use as protective coatings in a variety of industrial applications (Wayne and Sampath 1992).

The initial development of thermal spray processing parameters by SUNY was concentrated on these systems. The coatings selected for the initial screening were Metco 71 VF-NS-1 and Tribaloy® T-800, by plasma spray; and Tribaloy® T-400, Tribaloy® T-800, Stellite® 6, and Sylvania Osram 150A, by HVOF process. As the project progressed, additional materials were prepared and tested.

Processing Condition Development

The plasma spray equipment used in the current study was the 9MB gun from Sulzer Metco, Inc., Westbury, NY. Argon was the primary gas and a Plasma Technic Twin 10 was the powder feeder. The HVOF equipment was a Jet Kote 2 system from Stellite® Coating Co., Goshen, IN.

Thermal spray coatings were produced by SUNY for ultrasonic cavitation screening. The coatings were applied by plasma spray and HVOF methods onto mild steel plates. The panels were SAE[6] 1020 cold rolled steel, 0.10 in. thick sheared to approximately 0.625 x 0.625 ins. The panels were cleaned with acetone or alcohol and roughened by grit blasting. The initial grit blast was performed with 60 aluminum oxide grit at 60 psi using a suction-type grit blast cabinet. Coating delamination was observed during testing on many of the samples, which was attributed both to edge effects due to small sample size and inadequate surface roughness of the substrates. To alleviate this problem, 45-degree chamfers of approximately 0.625 in. were ground into the edges of the panels; after cleaning, the panels were grit blasted with 24 aluminum oxide grit at 80 to 100 psi. This produced a surface roughness of at least 300 microinches Ra using a 0.030 in. waviness cutoff with a 0.100 in. travel as measured using a Mitutoyo Surftest III surface profilometer. This corresponds to a surface profile of between 0.001 to 0.002 in. No further delamination was observed on panels prepared in this way. The spray coatings were deposited within 4 hours after the grit blasting. If more than 4 hours passed, the samples or substrates were grit blasted again before coating.

The surface roughness was measured using a Mitutoyo Surftest III surface profilometer. The machine consists of a readout unit and a measuring unit connected by electrical cable. The readout unit provides power and has an analog dial with several sensitivity settings. The measuring unit has a motor-mounted arm and a travel adjustment. A shoe and a needle are mounted on the measurement end of the arm. The shoe rides on the surface to be measured and the needle, in front of the shoe, is pressed onto the surface with a constant load of several grams. The vertical travel of the needle is detected and these data are sent to the measurement unit, processed by the electronics, and read out on the analog dial. The unit was operated according to established procedure. Cutoff and travel length are chosen to provide reasonable sensitivity for the surface roughness required for thermal spray coatings.

[6] SAE: Society of Automotive Engineers.

Advanced Weld Material Samples

Weld samples of CaviTec® and Hydroloy® 914 were prepared by USACERL. Carbon steel plate 1/4 in. thick was welded with CaviTec® and Hydroloy® 914 flux-core filler metal. A uniform single layer was deposited on the plate in the flat position with a gas metal arc welding (GMAW) system. The shield gas was argon and the welding parameters were those recommended by the wire manufacturer. For the CaviTec®, the welding current was 125 amps and the voltage was 30 volts. For the Hydroloy® 914, the welding current was in the range 100 to 140 amps and the voltage was in the range 16-18 volts. The samples of Norem® and D-Cav® were prepared by the manufacturers using the GMAW process.

Ultrasonic Cavitation Testing

Coatings were tested by SUNY using an ultrasonic test apparatus, a Branson Power Sonic Company model Sonifer Cell Disrupter Model 350 with an exponential horn. The test used a modified ASTM G 32 configuration with the sample placed below the tip of the ultrasonic horn (see Figure 4B). The sprayed panels were tested in distilled water at 68 °F. The temperature was maintained by a chilled water coil. The test parameters on the ultrasonic apparatus were as follows: frequency, 20 kHz; amplitude, 50 micrometers; and separation distance, 0.025 in.

The samples were weighed before the test and after 60 and 120 minutes of testing. These screening tests were used to refine the specimen preparation and spray parameters.

Cavitating Jet Testing

This method uses a submerged cavitating jet to erode a test specimen placed in the jet's path. Water is supplied through a cartridge-style filter to a positive-displacement pump rated at 10,000 psi, and operated at 4000 psi and 6000 psi in the current tests. Power is supplied by a 25 horsepower electric motor. A flow-control valve sets the operating pressure and flow, and a bypass valve provides a safety backup. An unloading valve is used to temporarily interrupt the test so specimens can be removed and weighed. Gages display inlet pressure and discharge pressure for system operations and accumulated hours of operation for system maintenance. The pump discharge is connected with high-pressure stainless steel piping to the stainless steel test chamber, which is approximately

18 in. wide, 18 in. long and 18 in. deep. Transparent windows are provided for observation of the specimen. A safety interlock on the test chamber lid prevents activation of the pump when the test chamber is open. The test chamber includes an adjustable specimen holder and an adjustable nozzle. The nozzle contains an internal centerbody. Flow downstream from this centerbody and the low pressure associated with the high-velocity jet produce a central region of intense cavitation that is channeled by the jet onto the test specimen. In this study, the test specimen weight was measured with an electronic single-pan scale and test duration was measured with an electronic timer.

A consistent test procedure is followed for each of the comparative cavitation tests. A "blank" specimen is inserted in the specimen holder, and the test chamber lid is secured. The inlet water pressure is checked, the bypass valve closed, the flow control valve is opened, and the pump is started. The flow control valve is slowly closed until the desired operating pressure is achieved. The flow and pressure control settings are maintained as the pump is stopped. An undamaged specimen is weighed, and the weight is recorded in the test log book. The "blank" specimen is replaced with the test specimen, and the distance between the nozzle and test specimen is adjusted if necessary. The electronic timer and the pump are simultaneously activated. Periodically throughout the test, the test specimen is removed, dried, weighed, and then returned to the test chamber and tested further following a similar procedure as outlined above. Three tests were conducted on each sample and the results were averaged. The testing was conducted at the TVA Engineering Laboratory, at Norris, TN.

Mechanical Testing

Testing of the mechanical properties of the thermal spray coatings conducted by SUNY included bond strength and microhardness. The bond strength test used was a modified version of the ASTM C 633 bond strength test. In this test a coating is applied to the butt end of one surface of a 1.0 in. diameter slug. This surface is then glued to the uncoated butt-end surface of another slug. The glued assembly is then pulled apart and the bond strength is recorded. This datum is then converted into pounds per square inch (psi). The modification of the ASTM C 633 test procedure used in this study is that the coatings were approximately 0.018 in. thick; ASTM C 633 calls for coatings 0.025 in. thick. The reason for this modification was that these coatings exhibit a reduction of bond strength when applied to thickness greater than 0.020 to 0.025 in. thick.

Hardness testing was conducted using a Wilson hardness test machine. The hardnesses were measured in accordance with the manufacturer's instructions. The surfaces were ground with 240 grit, then 320 grit, then 600 grit silicon carbide paper to provide a smooth surface for the indentation. The correct indenter for the hardness was chosen, and in most cases it was the "N" brale on the 15T scale. The scale refers to the weight used to make the indentation. The major and minor loads were then applied and the reading was taken from the digital readout and converted to the Rockwell C (R_C) scale.

Erosion Testing

A slurry wear test developed by the U.S. Bureau of Mines was used to determine the wear rate of thermal sprayed coatings deposited by both the plasma spray and HVOF processes (Madsen 1990). Samples of Stellite® 6, Tribaloy® T-400 and Tribaloy® T-800 along with control samples of 304 stainless steel, and ASTM A 572 carbon steel were tested in the slurry wear apparatus. All samples were cleaned and weighed before insertion into the test apparatus. Each specimen was electrically isolated (to eliminate galvanic corrosion effects) from the other samples by using ultrahigh molecular weight (UHMW) polyethylene specimen blanks. The slurry erosion test consisted of running 2 weight percent silica sand slurry (ASTM C-109) through the specimen chamber of the slurry wear apparatus. The impeller turned at 2256 revolutions per minutes (rpm), which yielded a nominal slurry velocity of 15.6 m/s. The test was set up to be a single pass test. That is, the slurry was not recirculated. The temperature of the water was 11 °C. The test was interrupted at 10, 30, and 60 minutes to clean and weigh the test specimen. The change in weight was determined and converted to a linear erosion rate based on the density of the material. For the thermal spray coatings, a density of 95 percent of the theoretical density was used in the calculations to determine volume loss.

6 Results and Discussion

Processing Condition Development

Development of thermal spray processing parameters by SUNY initially focused on Metco 71 VF-NS-1 and Tribaloy® T-800 by plasma spray; and Tribaloy® T-400, Tribaloy® T-800, Stellite® 6, Sylvania Osram 150A by HVOF process.

The erosion rate and delamination are affected by the spray parameters. In the field application of the coatings, the least flexible parameter is the spray distance. This is due to manual operation of the gun during the spray application. The spray distance was identified early as a critical parameter. The spray distance was varied by 6 in. for HVOF process and by 3 in. for the plasma spray coatings, which is a greater amount than would normally occur in the field. The optimum spray distance was determined and reported in Tables 8 and 9.

Surface preparation is critical to the success of the coating. Grit blasting provides compressive surface stresses, surface features to improve mechanical interlocking of the coating to the surface, and increased contact area. The grit shape and size determines the surface roughness achieved by abrasive blasting. The abrasive blast media recommended was 24 grit aluminum oxide. It should be used once and not recycled. The resulting surface, measured using a Mitutoyo Surftest III surface profilometer, had a roughness of at least 300 microinches R_a using a 0.030 in. waviness cutoff with a 0.100 inch travel.

The processing parameters for plasma spray and HVOF process were developed by SUNY, and are presented in Tables 8 and 9. Additional coatings were prepared with combustion spray and two arc processes. Standard recommended processing parameters within the tolerances allowed by the manufacturers were used. The surface preparation and processing parameters are critical to the ultimate performance of the coating. Therefore, it is recommended that the processing parameter values shown in Table 9 be used for these coating systems when using the Jet Kote HVOF system.

Table 8. Plasma spray materials and processing parameters.

	Metco 71 VF-NS-1	Tribaloy® T-800
Gun & Components		
Gun Type	Metco 9MB with air jets	Metco 9MB with air jets
Nozzle	728 or 708	733 or GP
Powder Port	Number 5	Number 2
Gases		
Primary	Argon	Argon
Supply Pressure (psi)	100	75
Flow (SCFH)	125	150
Secondary GSA		
Supply Pressure	50	75
Flow rate (SCFH)	15	15
Power		
Amperage (amps)	900	550
Voltage (volts)*	50 to 55	80
Powder Feed		
Feeder Type	Plasma Technic Twin 10C or Metco 3MP	Plasma Technic Twin 10C or Metco 3MP
Powder Feeder Gas	Argon	Argon
Carrier Flow (SCFH)	8	5.5
Feed rate (lb/h)	6	8
Air Jets		
Configuration	Parallel	Parallel
Pressure (psi)	75	50
Spray Distance		
Distance (inches)	4 to 4.5	6

* Voltage is adjusted by varying the secondary gas +/- 5 SCFH

The principal HVOF operating parameters to be controlled are (1) the pressure and flow rates for the fuel gas and oxygen, (2) the carrier gas flow, and (3) the powder feed rates. HVOF spray systems manufactured by Miller Thermal Inc., Metco Inc., and others, also can produce high-quality coatings. However, the processing parameters depend on the spray equipment and the material being sprayed. The processing parameters for a particular material should be determined in consultation with the spray equipment manufacturer and powder supplier. These parameters should be verified by spraying a test sample and performing metallographic examination of the microstructure. Based on the results of the analysis, minor changes in the processing parameters may be needed. Two or three iterations may be required to fully optimize the processing parameters. The optimization should not require more than 1 day.

Table 9. HVOF materials and spray parameters.				
	Tribaloy® T-400	Tribaloy® T-800	Stellite® 6	Sylvania Osram 150 A
Gun & Components				
Gun Type	Jet Kote 2	Jet Kote 2	Jet Kote 2	Jet Kote 2
Nozzle	6 inch	6 inch	6 inch	6 inch
Main Flame				
Fuel gas	Propylene	Propylene	Propylene	Propylene
Supply Pressure				
Oxygen (psi)	120	120	120	120
Fuel (psi)	100	100	100	100
Gun Pressure				
Oxygen (psi)	60	65	65	67
Fuel	75	80	72	80
Hydrogen Pilot				
Supply Pressure (psi)	25	25	25	25
Flow (SCFH)	10	10	10	10
Oxygen Pilot				
Supply Pressure (psi)	120	120	120	120
Flow (SCFH)	10	10	10	10
Powder Feeder				
Plasmadyne High Pressure				
Powder Feeder Gas	Nitrogen	Nitrogen	Nitrogen	Nitrogen
Carrier Flow (SCFH)	65	70	67	75
Feed Rate (lb/h)	10	10	10	10
Spray Distance				
Distance (inches)	8	7	6	8

Ultrasonic Cavitation Screening Results

Over 16 coatings were produced by thermal spray for ultrasonic cavitation resistance screening. The qualitative assessment of high, medium, and low resistance were used to indicate relative performance among the coatings. This qualitative assessment scale was used due to the limited and preliminary nature of the data. At the time of the tests not enough data had been collected to ensure statistical confidence for reporting purposes. The results of this preliminary screening are shown in Table 10. Additional screening was conducted on materials with high cavitation resistance.

Table 10. Cavitation resistance screening of thermal spray coatings by ultrasonic cavitation testing.

HVOF Coatings	Cavitation Resistance
Tribaloy® T-400	High
Tribaloy® T-800	High
Stellite® 6	High
Sylvania Osram 150 A	High
Tribaloy® T-700	Medium
Stainless Steel Type 316	Medium
Nickel 5% - Aluminum	Medium
Nistelle D	Low
Arc Plasma Coating	
Metco 71 VF-NS-1	High
Tribaloy® T-800	High
Sylvania Osram 150 A	High
Tribaloy® T-400	Medium
Stainless Steel Type 431	Medium
Nistelle® C	Low
Nistelle® D	Low
Stellite® 6	Low

Coatings on panels welded with stainless steel showed little performance difference compared to coatings on mild steel panels (Table 11). The stainless steel weld overlay was used to simulate the weld repair used in the field repair of cavitation damage.

Table 11. Cavitation resistance screening of Tribaloy applied by HVOF.

Material	Welded Stainless Steel Substrates 60 minute average weight loss	Mild Steel Substrates 60 minute average weight loss
Tribaloy® T-400	35.4	36.2
Tribaloy® T-800	22.8	23.6

The coatings showed sensitivity to the spray parameters, surface preparation, and thickness of the deposit. For example, Tribaloy® T-800 sprayed by HVOF showed a reduction in weight loss of over 50 percent for a coating 0.020 in. versus a coating of 0.040 in. deposited using the same parameters and powder lot. The powder type was JJ-558, size 325D, lot 3941-5. The results of Tribaloy® T-800 alloy sprayed at two deposit thicknesses showed that the 0.020 in. thick coating had lower weight loss (higher cavitation resistance) during ultrasonic cavitation testing than those sprayed to a thickness of 0.040 in. (Table 12). This

was used to specify the total thickness of spray coating in the field to between 0.018 and 0.025 inches.

Table 12. Cavitation resistance screening of Tribaloy® T-800 applied by HVOF.

Thickness	Cumulative Weight Loss 30 Min. (mg)	Cumulative Weight Loss 60 Min. (mg)	Cumulative Weight Loss 120 Min.(mg)
0.040 inches	36.0	62.9	110.5
0.020 inches	14.5	23.1	29.7

Three samples of each material were screened for cavitation rate using the vibratory cavitation apparatus. The average and standard deviation are shown in Tables 13 and 14. In order to compare the variability between material systems with widely different mean values, the normalized standard deviation (the standard deviation divided by the mean, as a percentage) was also determined. The variability in weight loss among ultrasonic tests for each material varied. The typical variability would be expected to be less than 10 percent. This was accentuated by changes in the spray parameters. High variability was seen in the tungsten-carbide-based materials—Sylvania Osram 150A applied by HVOF and the Metco 71 VF-NS-1 applied by plasma spray. Tribaloy® T-400 applied by plasma spray also showed high variability in the ultrasonic cavitation results. The least variability was observed for Stellite® 6 coatings applied by HVOF. Coatings prepared in the laboratory that exhibit low variability in cavitation protection are therefore less sensitive to slight variations in the coating process and probably would be more forgiving during field application.

The averaged results of cavitation screening used for the full range of materials are shown in Table 15. The full results are presented in Appendix A. The best performing material prepared both by HVOF and plasma spray processes was Stellite® 6. The HVOF-prepared materials had significantly lower cavitation wear (material loss) than the plasma-sprayed materials, for example 6.43 mg for Stellite® 6 by HVOF versus 35.5 mg by plasma spray, and 47.30 mg for Tribaloy® T-400 by HVOF versus 105.15 mg by plasma spray. The lower cavitation rates for HVOF coatings compared to plasma spray coatings is consistent with results reported by other researchers (Soares et al. 1994 and Kreye et al. 1995). The lower cavitation rates for coatings prepared by the HVOF process may be attributable to the higher particle impact velocities and higher densities of HVOF-prepared coatings as compared to the plasma sprayed coatings (Irons 1992).

Table 13. Ultrasonic cavitation screening of HVOF Coatings.

	60 Minutes			120 Minutes		
Material	Average wt. Loss (mg)	Standard Deviation	Normalized Standard Deviation (Percent)	Average wt. loss (mg)	Standard Deviation	Normalized Standard Deviation (Percent)
Tribaloy® T-400 @ 0.020 inches	35.4	5.3	14.8	47.3	3.7	7.8
Tribaloy® T-800 @ 0.040 inches	63.2	3.9	6.1	111.6	23.0	20.6
Tribaloy® T-800 @ 0.020 inches	22.8	3.6	15.5	29.4	2.4	8.0
Stellite® 6 @ 0.020 inches	4.0	0.25	6.2	6.4	0.5	7.8
Sylvania Osram 158 @ 0.020 inches	47.7	12.7	26.6	119.0	17.3	14.6

Table 14. Ultrasonic cavitation screening for plasma spray coatings.

	60 Minutes			120 Minutes		
Material	Average wt. Loss (mg)	Standard Deviation	Normalized Standard Deviation (Percent)	Average wt. loss (mg)	Standard Deviation	Normalized Standard Deviation (Percent)
Metco 71 VF-NS-1 @ 0.020 inches	64.0	7.8	12.2	229.7	17.9	78.2
Tribaloy® T-800 @ 0.020 inches	65.0	5.4	8.3	97.6	6.9	7.0
Tribaloy® T-400 @ 0.020 inches	60.4	10.8	17.9	105.2	19.9	18.9
Stellite® 6 @ 0.020 inches	19.2	1.8	9.4	35.5	4.1	11.4

Table 15. Ultrasonic cavitation screening.

Process/Material	Avg. wt loss 60 minute (mg)	Avg. wt loss 120 minute (mg)
Steel Reference		
SAE 1020	2.47	6.6
HVOF		
Stellite®-6	4.03	6.43
Tribaloy® T-800 (0.020 inch thick)	22.87	29.40
NOREM® HVOF	24.00	37.00
Tribaloy® T-400	35.43	47.30
WC/Co (Sylvania Osram 150A)	47.67	119.00
Tribaloy® T-800 (0.040 inch thick)	63.27	111.67
Tribaloy® T-700	127.33	182.33
Ni-5% Al alloy	141.00	167.00
316 Stainless Steel	145.33	194.33
Nistelle® D	182.33	247.67
Plasma Spray		
Stellite®-6	19.2	35.5
NOREM®	35.33	48.33
NiCrBSi	35.33	48.33
Tribaloy® T-400	60.38	105.15
WC /Co (Metco 71 VF-NS-1)	64.00	229.67
Tribaloy® T-800	64.80	97.63
316 Stainless Steel	68.00	99.67
SS 430	95.67	146.33
Combustion Spray		
Al-Zn	147.33	227.33
Two-Wire Arc		
CaviTec®	117.33	172.67
430 Stainless Steel	120.00	155.00
316 Stainless Steel	122.33	197.33

Cavitating Jet Test Results

Coatings prepared by HVOF, plasma spray, and other thermal spray techniques were tested using the cavitating jet apparatus. The samples were prepared by SUNY using the same process parameters used for the ultrasonic cavitation screening samples. The test results are shown in Tables 16-17. The results for

advanced weld alloys are presented in Table 18. The cavitation resistance results of the coated samples prepared by HVOF, plasma spray, combustion spray, and two-wire arc using the cavitating jet apparatus were lower than for the stainless steel reference panel, which had an average wear rate of 3.2 mg/h. The cavitation rate (3.2 mg/h) for welded 308 stainless steel was lower than the 9.8 mg/h rate obtained using the cavitating jet apparatus at the same 4000 psi test condition (see Table 4; March and Hubble 1996). This discrepancy could have arisen from differences in the cavitating jet nozzle or in the quality of the weld samples. Additionally, the cavitation rate for 308 stainless steel weld, measured using the ultrasonic cavitation test, was reported in another study to be 15 mg/h (Simoneau 1991). For purposes of comparing the cavitation resistance of thermal spray coating materials and techniques, the value for stainless steel obtained in the current study with the cavitating jet apparatus was used.

The cavitation rate of the welded 308 stainless steel reference was 3.2 mg/h. The cavitation rates of all coatings prepared either by the HVOF or plasma spray processes were higher than the welded 308 stainless steel reference. The best-performing coating material prepared either by HVOF or plasma spray was Stellite 6, with a cavitation rate of 11.7 mg/h (HVOF) and 13.6 mg/h (plasma). The lower cavitation rate of Stellite 6, as compared to other HVOF coatings, may be due to its wider process capabilities to provide quality coatings. This was confirmed by the spray technician, who reported that it was easier to obtain high-quality coatings with Stellite 6 than with the other materials. The manufacturer's data for Stellite 6 is reprinted in Appendix B.

The HVOF coatings generally had lower cavitation rates than the plasma spray coatings. This is consistent both with the ultrasonic cavitation screening results reported in the previous section and with the results of other researchers (Soares et al. 1994; Kreye et al. 1995).

Table 16. Results of cavitating jet testing of HVOF coatings at 4000 psi.

Sample	Wt. Loss (mg/h)	Cavitation Rate vs 308 Weld
308 Stainless Steel -Weld	3.2	1.00 X
Stellite® 6	11.7	3.6 X
NOREM®	16.9	5.3 X
Tribaloy® T-400	18.9	5.9 X
Tribaloy® T-800	23.8	7.4 X
WC/Co (Metco 71 VF-NS-1)	35.3	11.0 X
WC/Co (Sylvania Osram 150 A)	49.0	15.3 X

Table 17. Results of cavitating jet testing of plasma spray coatings at 4000 psi.

Sample	Wt Loss (mg/h)	Cavitation Rate vs 308 Weld
308 Stainless Steel -Weld	3.2	1.00 X
Stellite® 6	13.6	4.3
316 Stainless Steel	26.2	8.2
Tribaloy® T-800	31.0	9.7
NOREM®	39.5	11.0
WC/Co (Sylvania Osram 150A)	58.0	12.3
Ni Alloy	94.7	29.6
430 SS	Fail	----
Tribaloy® T-400	Fail	----

Table 18. Summary of cavitation results from other researchers

Source	Material	Test	Time to failure (Hours)	Relative Cavitation Rate
March and Hubble (1996)	308 SS Weld	Cavitating jet		1.0
March and Hubble (1996)	Carbon Steel	Cavitating jet		1.6
Baker (1992)	308 SS Weld	Venturi	2075	1.0
Baker (1992)	Carbon Steel	Venturi	1038	2.0
Baker (1992)	Metallized Tribaloy T-400	Venturi	565	3.7

Based the cavitation testing results reported here and by other researchers (Table 18) the cavitation rate of carbon steel is between 1.6 and 2.0 times higher than the cavitation rate of the welded 308 stainless steel reference. The cavitation rate of Stellite 6 applied by the HVOF process was 3.6 times higher than the cavitation rate of the welded 308 stainless steel reference.

Only two materials prepared by combustion flame spray process survived the cavitation jet test. These were the NiCrBSi alloy and 316 stainless steel. Both had significantly higher cavitation rates than the welded stainless steel reference material. All other materials prepared by combustion flame spray and the two-wire arc processes failed due to delamination of the coating during testing. This includes CaviTec®, a wire designed for use in transferred arc welding but applied using a two-wire arc thermal spray system in this test.

Some of the coatings that survived the ultrasonic cavitation screening test (albeit with high cavitation rates) failed by delamination when tested by cavitating jet. This result indicates that the failure mode may be different for each of the two tests. This interpretation is consistent with the conclusions that

ultrasonic cavitation testing did not predict the field performance of polymer coatings whereas the cavitating jet testing did (Cheng, Webster, and Young 1987). Therefore, the researchers in the current study concluded that cavitating jet testing is preferred to ultrasonic cavitation testing to determine the cavitation resistance of materials.

Samples of advanced iron-based weld alloys were prepared and tested using the cavitating jet apparatus at both 4000 and 6000 psi. The advanced weld alloys showed superior cavitation resistance compared to welded 308 stainless steel (Table 19). The cavitation rates at 4000 psi ranged from 1.0 mg/h for NOREM® to 2.6 mg/h per for CaviTec®. All materials performed very well and had cavitation rates lower than the 308 stainless steel reference panel (3.2 mg/h).

Table 19. Results of cavitating jet testing of other thermal spray coatings at 4000 psi.

Sample	Alloy	Process	Weight loss (mg/h)	Cavitation Rate vs 308 Weld
308 SS - Weld	308 Stainless Steel	Weld	3.2	1.00 X
Eutectics 21032S	50 Ni + 20 Fe + 20 Mo + 10 Ti	Combustion Powder	58.0	18.1 X
Eutectic 29011	316 Stainless Steel	Combustion Powder	499.4	155.9 X
Al/Zn	Zn + 15 Al	Combustion Powder	Fail	---
Eutectics 29202	Al	Combustion Powder	Fail	---
Arc Sprayed 430 SS	430 Stainless Steel	Two Wire Arc	Fail	---
CaviTec® W25	Advanced Alloy	Two Wire Arc	Fail	---
316 SS	316 Stainless Steel	Two Wire Arc	Fail	---

As noted above, cavitation rates also were measured at a test pressure of 6000 psi. Due to the use of different nozzles, there was variation in values of the stainless steel in different tests at 6000 psi. This required the results be normalized to the 308 stainless steel reference samples tested at the same time. At the 6000 psi test pressure, the cavitation rates were higher than at 4000 psi, ranging from 3.1 mg/h to 4.3 mg/h. All of the materials tested performed very well, with cavitation rates only 0.2 to 0.3 times that of the welded 308 stainless steel reference samples. The tests were not able to identify significant differences between these advanced weld alloys; a larger number of samples would be required to establish statistical variation and ranking. The end user's choice of one material over another would depend on additional factors such as field weldability and cost.

Mechanical Testing Results

Testing of the mechanical properties of the thermal spray coatings was conducted by SUNY. This included hardness and bond strength measurements as shown in Table 20. The cavitation rate determined in the cavitating jet test are included in Table 21 for comparison. The hardness ranged from 36 – 55 R_c for the HVOF and plasma spray materials, with NiCrBSi having the highest hardness. The hardnesses of the two-wire arc coatings were lower, ranging from 26 – 29 R_c. The hardness of the Al-Zn coating applied by combustion spray was substantially lower and measured on a different scale, with a value of 29 R_h. The bond strengths of the coatings ranged from 4300 to 7600 psi. Tribaloy® T-400 and Stellite® 6 prepared by HVOF had the highest bond strengths at 7600 psi and 7500 psi, respectively. The bond strength of the combustion spray and two-wire arc spray coatings were significantly lower, ranging from 2100 to 3900 psi.

Table 20. Mechanical properties of thermal spray coatings.

Material	Hardness	Bond Strength (psi)	Cavitation Rate (mg/h)
HVOF			
Tribaloy® T-400	40 Rc	7600	18.9
Tribaloy® T-800	38 Rc	6400	23.8
NOREM®	42 Rc	5500	16.9
Stellite® 6	41 Rc	7500	11.7
WC/Co (Metco 71 VF-NS-1)	54 Rc	6200	35.3
WC/Co (Sylvania Osram)	51 Rc	5700	49.0
Plasma Spray			
Tribaloy® T-400	46 Rc	6500	Failed
Tribaloy® T-800	43 Rc	4300	31.
NOREM®	46 Rc	5200	39.5
Stellite® 6	41 Rc	6800	13.6
WC/Co (Metco 71 VF-NS-1)	49 Rc	5800	58.0
NiCrBSi alloy	55 Rc	6400	94.7
430 Stainless Steel	36 Rc	4300	Failed
Combustion Spray			
Al-Zn	29 Rh	2100	Failed
Two-Wire Arc			
430 Stainless Steel	26 Rc	3700	Failed
316 Stainless Steel	28 Rc	3900	Failed
Linear Regression			
r	0.750	-0.510	
r^2	0.563	0.260	

Table 21. Results of cavitating jet testing of weld alloys.			
Alloy	**Wt. Loss (mg/h)**	**Test Pressure (psi)**	**Cavitation Rate vs 308 Weld**
308 Stainless Steel	3.2	4000	1.0 X
NOREM®	1.0	4000	0.3 X
D-CAV®	1.3	4000	0.4 X
Hydrolo® 914 Sample A	1.7	4000	0.5
Hydroly® 914 Sample B	2.0	4000	0.6 X
CaviTec® Sample A	2.3	4000	0.7 X
CaviTec® Sample B	2.6	4000	0.8 X
CaviTec® Sample A	3.1	6000	0.2 X
CaviTec® Sample B	3.4	6000	0.3 X
D-CAV®	3.4	6000	0.3 X
Hydroloy® 914	3.5	6000	0.3 X
NOREM®	4.3	6000	0.3 X

Linear regression analysis was performed on the hardness and bond strength data with respect to the cavitating jet cavitation rate data for coatings that survived. The analysis showed that the cavitation rate increased with the hardness. The values of the correlation coefficient, R, and the square of the correlation coefficient, R^2, were 0.750 and 0.563 respectively. Although there was more scatter in data, the cavitation rate was found to decrease with increasing bond strength. The calculated values R and R^2 were -0.510 and 0.260 respectively. Two plasma sprayed coatings and all combustion sprayed and two-wire sprayed samples that failed the cavitating jet test were not included. The combustion spray and two-wire arc samples had significantly lower hardness and bond strength. Therefore, from this analysis, bond strength was a better predictor of cavitation resistance than hardness. In order to fully confirm the statistical relationships, substantially greater number of samples would have to be tested. However, it must be noted that neither individual property can serve as the sole predictor of a material's cavitation resistance. The cavitation resistance depends on the interaction of additional material properties.

The results showed that the current state of the art in thermal spray processes and materials cannot provide a coating that is much better in resisting direct cavitation damage than a welded steel material. Therefore, direct cavitation damage should continue to be repaired using a fusible material by a welding process. For severe cavitation, which is defined as more than 1/8 inch damage to austenitic stainless steel in 6 months or less, welding an advanced iron based alloy such as NOREM®, D-CAV®, CaviTec® and Hydroloy® 914 should be considered for use due to their superior cavitation resistance.

Erosion Results

The results of the slurry erosion wear test are presented in Table 22. The results show that three thermal spray coatings applied by the HVOF process performed better than the carbon steels (ASTM A572, ASTM A514, AISI 4340) and the stainless steel reference materials. The slurry erosion rate for stainless steels ranged from 9.2 to 11.5 mm^3. The HVOF coating with the lowest volume loss after 1 hour was WC-12Co, with 1.06 mm^3. The volume loss after 1 hour for the Stellite® 6 and Tribaloy® T-800 coatings were 5.33 and 6.76 mm^3, respectively. This loss is lower than the 1-hour volume loss of 19.70 mm^3 for ASTM A572, 12.36 mm^3 for ASTM A514, 11.7 mm^3 for 304 stainless steel, and 7.82 mm^3 for AISI 4540. The Tribaloy® T-400 and Tribaloy® T-800 coatings applied by plasma spray did not perform as well as the reference alloys. Visual inspection of the Tribaloy® T-800 prepared by plasma spray, after 1 hour of slurry erosion wear testing, showed penetration of the coating and wear of the substrate. Therefore, HVOF coatings may be considered for use in hydraulic equipment to protect against erosion.

Linear regression analysis was performed on the erosion data with respect to the cavitating jet cavitation rate results as well as to the hardness and bond strength results. The analysis showed poor correlation between the slurry erosion rate and the results of the cavitation test, with values of R= -0.535 and of R^2 = 0.286, respectively. The analysis showed that the slurry erosion rate increased as bond strength increased, with R and R^2 values of 0.698 and 0.457, respectively. The slurry erosion rate was found to decrease as hardness increased, with R and R^2 of -0.713 and 0.535, respectively. Based on this limited analysis of four coating systems applied by HVOF, materials with high hardness showed the best correlation with low slurry erosion wear rates.

Table 22. Results of slurry erosion wear test.

Material	Process	Theoretical Density Cast (gm/cm^3)	Average Mass Loss 10 Min. (mg)	Average Mass Loss 30 Min. (mg)	Average Mass Loss 60 Min. (mg)	Standard Deviation Mass Loss 60 Min. (mg)	Average Volume Loss* 60 Min. (mm^3)	Relativ e Volume Loss vs ASTM A 572
ASTM A572	Cast	7.80	24.0	75.9	153.7	8.1	19.70	1.0
ASTM A514	Cast	7.85	16.0	48.4	97.0	8.4	12.36	0.6
AISI 4340	Cast	7.81	11.2	32.2	61.1	7.1	7.82	0.4
304 Stainless Steel	Wrought Alloy	7.91	14.7	41.6	88.4	6.0	11.17	0.6
316 Stainless Steel	Wrought Alloy	7.91	14.1	39.9	75.2	1.4	9.50	0.48
308 Stainless Steel	Weld Overlay	7.91	12.2	37.7	73.0	11.5	9.22	0.46
310 Stainless Steel	Weld Overlay	7.91	14.0	44.8	8.37	16.0	10.58	0.53
Tribaloy® T-400	Plasma Spray	9.00	28.6	77.8	144.9	1.9	16.95	0.9
Tribaloy® T-800	Plasma Spray	8.65	49.4**	121.1**	27.2**	65.4**	27.2**	1.4
Tribaloy® T-400	HVOF	9.00	19.6	60.1	114.5	109	13.39	0.7
Tribaloy® T-800	HVOF	8.65	13.8	32.8	55.6	10.7	6.76	0.3
Stellite® 6	HVOF	8.38	7.7	23.0	42.5	2.4	5.33	0.3
WC-12Co	HVOF	13.2	3.7	7.4	13.3	1.6	1.06	0.13

* Assumes 95 percent of theoretical density for coatings

** For two of four samples, the coating was penetrated and the substrate attacked

7 Field Demonstration

The Raccoon Mountain Demonstration Site

The field demonstration of HVOF thermal spray coatings was conducted in September 1996 at the TVA's Raccoon Mountain Pumped-Storage Plant, Chattanooga, TN. The plant consists of four Francis pump/turbine units (Figure 8), each with a rated generating capacity of 392 MW at 1020 ft head. The pump/turbines are a reversible Francis type with a vertical shaft, manufactured by Allis Chalmers. The runner diameter is 16 ft, 7 in. The original vane material was ASTM A 296 CA6NM, a grade of martensitic stainless steel. This material has relatively high strength and has a cavitation rate of 15 mg/h, which was the same as 308 stainless steel (see Table 1; Simoneau 1991).

Two materials are used by the TVA for weld repair depending on the degree of cavitation. HQ 914 is used in areas of high cavitation, such as the vanes; 308 stainless steel is used in areas of low cavitation, such as the cone. Since Hydroloy 914 has been used, repairs of severe cavitation are only necessary every 3 to 4 years. This is in contrast to TVA's earlier experience using 308 stainless steel weld alloy, in which repairs were necessary every year. Thermal spray coatings were applied during the field demonstration on top of weld-repaired areas of 308 stainless steel and areas of Hydroloy 914.

Demonstration Materials and Field Application Procedure

The HVOF coating systems applied in the field demonstration were Stellite® 6 and Tribaloy® T-400. Stellite had the highest cavitation resistance in both ultrasonic and cavitating jet testing (11.7 mg/h). NOREM® (16.9) and Tribaloy® T-400 (18.9 mg/h) had similar cavitation wear rates. The results could not be differentiated statistically without testing a significant number of additional samples. Based on previous research (Baker 1994), as well as its greater availability, Tribaloy® T-400 was selected. The chemical and particle size analyses of the materials used in the demonstration are shown in Table 23 and Table 24.

The field demonstration was conducted by a contractor[7]. The HVOF unit used in the demonstration is trailer-mounted and can apply a coating 250 ft from the trailer without any modifications. This setup controls contamination because the powder feed unit and spray materials are stored and secured in the trailer and only the gun is in the work area. HVOF system used in the field was a Metco Diamond Jet (D.J.) HVOF system (Figure 9 and 10). This HVOF system was made by a different manufacturer than the one used in the laboratory testing. In contrast to the system used in the laboratory, the D.J. system does not have a pilot system to permit idling when a coating is not being applied. Both the Metco and Jet Kote HVOF systems are widely used in the thermal spray industry. Operating parameters have been established by the manufacturers of both HVOF systems for Stellite and Tribaloy alloys. When the coatings are applied using the appropriate operating parameters for the specific HVOF system, the quality of the coating should be equivalent.

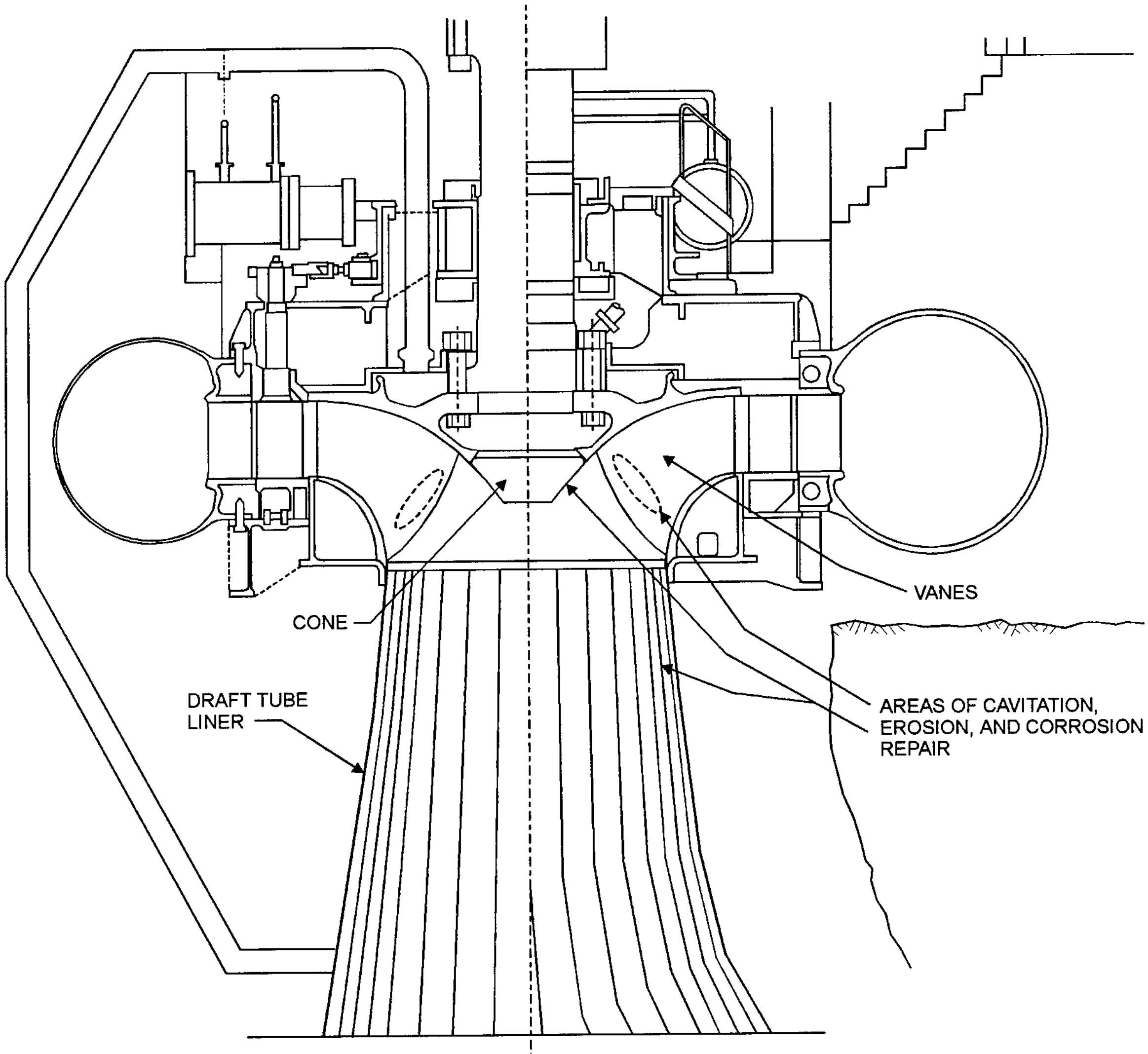
Table 23. Chemical analysis of materials used in field demonstration.

	C	Co	Cr	Fe	Mn	Mo	Ni	Si	W
Tribaloy® T-400	0.02	Bal.	0.77	0.51		28.92	0.32	2.61	
Stellite® 6	1.22	Bal.	28.61	2.07	0.30	0.08	2.23	1.10	4.95

Table 24. Particle size analyses for materials used in the field demonstration.

	+ 53 micron	53 microns < 44 microns	-325 microns
Tribaloy® T-400	0	0	100 %
Stellite® 6	0	1.99%	98.0%

[7] National Thermal Spray, Cypress, TX



Source: Karr et al. 1994.

Figure 8. Schematic of hydroelectric pump/turbine at Raccoon Mountain showing where HVOF coatings were applied.

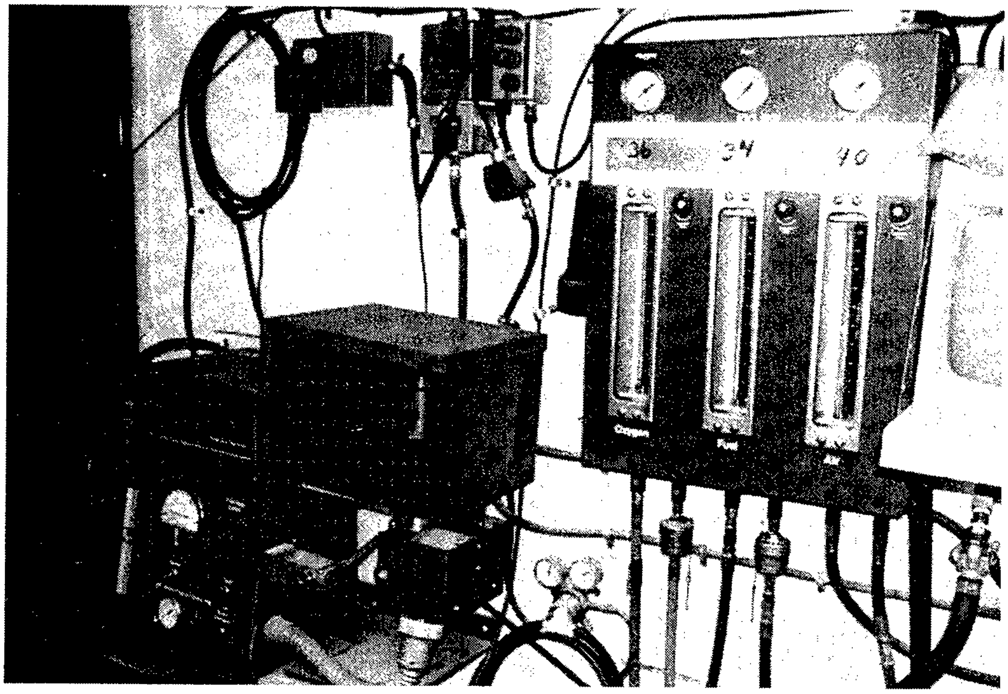


Figure 9. Thermal spray powder feed and gas flow control systems mounted in a mobile field trailer.

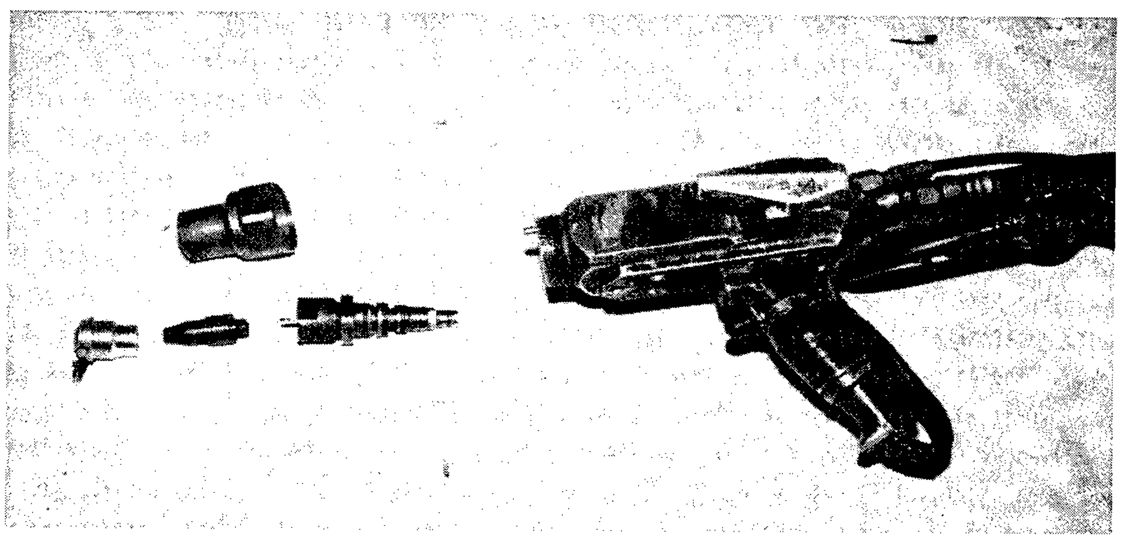


Figure 10. HVOF gun used in the field demonstration.

Table 25. Spray equipment parameters used during the field demonstration.

	Stellite® 6	Tribaloy® T-400
Gun & Components		
Gun	Diamond Jet	Diamond Jet
Injector	#3	#3
Shell	A	A
Insert	#3	#3
Siphon Plug	#2	#2
Air Cap	#2	#2
Main Flame - Field Conditions		
Fuel Gas	Propylene	Propylene
Oxygen pressure (psi)	150	150
Oxygen flow (Flow Meter Reading)	42	42
Fuel Pressure (psi)	100	100
Fuel flow (Flow Meter Reading)	40	40
Air Pressure	75	75
Air Flow (Flow Meter Reading)	60	60
Powder Feeder - Field Conditions		
Metco MJP		
Powder Hose	Red	Red
Carries Gas	Nitrogen	Nitrogen
Supply pressure (psi)	125	125
Flow, (Flow Meter Reading)	55-60	60
Pick-up Shaft	"E"	"E"
Air Vibrator Setting (psi)	20 psi	20 psi
Spraying - Desired Parameters		
Spray distance	6-8 in.	6-8 in.
Spray rate	3 lb/h	3 lb/h
Deposit efficiency	82%	82%
Thickness	20-25 mil	20-25 mil

Before application of the coating, the surface was grit blasted in accordance with SSPC 10 using virgin aluminum oxide grit. The pressure was at least 80 psi. Application of the coating was conducted within 4 hours after the grit blasting.

The spray parameters used during the field demonstration are listed in Table 25. Test patches of approximately 1 foot square of both the Stellite® 6 and Tribaloy® T-400 were successfully applied in the field by HVOF to the turbine vanes, cone, and draft tube liner. Weld repairs using 308 stainless steel were made to the cone and areas of mild cavitation, and repairs to the vanes and areas of severe cavitation using Hydroloy® 914 were conducted during the same outage as when the thermal spray coatings were applied. HVOF coatings were applied over these weld-repaired areas. Thickness measurements of coatings applied over weld-repaired with stainless steel could not be obtained using magnetic thickness gauges. The coating thickness was estimated from the

weight of the materials applied. The thickness was also measured using a micrometer on steel test panels that were sprayed at the same time as the turbine components. The average thicknesses of the Stellite® 6 and Tribaloy® T-400 test panels were 0.025 in. and 0.020 in., respectively.

Severe cavitation damage at a runner crown/vane intersection of the turbine is shown in Figure 11. The condition of the turbine cone is shown in Figure 12. The area coated included an area near the base of the cone which had been repaired by welding 308 stainless steel and an area above this that was carbon steel. The weld repair was done by TVA personnel prior to start of the demonstration. The same area of the cone is shown in Figure 13 after the Stellite® 6 was successfully applied by HVOF thermal spray process. Tribaloy® T-400 and Stellite® 6 were also successfully applied to the draft tube liner and turbine vanes by HVOF. The surface of the turbine vanes had been weld-repaired with Hydroloy® 914 while the draft tube liner was the original carbon steel. Problems reported by Lontz (1992) with the field application of HVOF coatings were not experienced during this field demonstration.

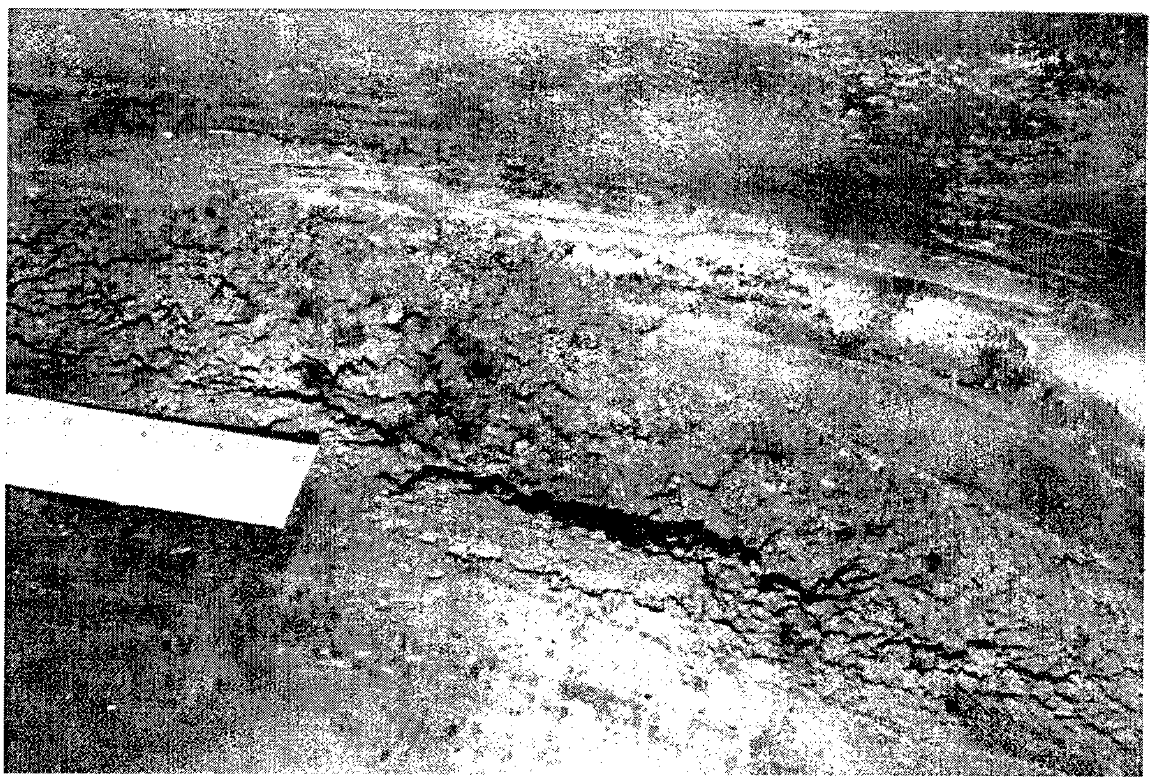


Figure 11. Severe cavitation at a vane/crown intersection on a Francis pump/turbine at the Raccoon Mountain plant.

Figure 12. Cavitation and corrosion on the cone of a Francis pump/turbine at the Raccoon Mountain plant.

Figure 13. Stellite® 6 applied by HVOF to the cone of a Francis pump/turbine at the Raccoon Mountain plant.

Test Samples From the Field Demonstration

During the field demonstration, the technician grit blasted and thermally sprayed 1/8 in. thick steel test panels. These panels were taken back to the laboratory where metallographic samples were prepared. The optical micrographs of the Stellite® 6 and T-400 are shown in Figures 14 and 15. The micrographs show good bonding at the interface between the substrate and the coating and very little porosity in the coating near the substrate (see Figure 14).

Both the Stellite® 6 and Tribaloy® T-400 coatings showed decreasing porosity in the coating from the coating surface to the coating/substrate interface. Greater porosity was observed in the Tribaloy® T-400 micrographs as compared to the Stellite® 6 (see Figure 15). This graduated porosity may decrease the cavitation resistance of the coating compared to a uniformly dense coating. Interconnected porosity could conceivably provide a continuous path through which water may reach the substrate. The presence of water at the coating/substrate interface may cause corrosion. However, the porosity in the sample field coatings was low near the substrate, and no continuous path was evident.

Initial Observations and Results

The demonstration at the TVA's Raccoon Mountain plant successfully showed the field applicability of the HVOF thermal spray process to deposit a good-quality coating inside a hydroelectric turbine. Visual observations of the turbine after 3 months of operation found the demonstration coatings to be intact and in good condition.

An additional inspection was conducted on 3 March 1997, 6 months after the field application of the coatings by the HVOF process. This interval represents 995 hours of the unit generating power and 1180 hours of the unit operating as a pump. At the time of this second inspection both the Stellite 6® and Tribaloy® T-400 coatings were intact and in good condition on the cone and throat ring of the hydroelectric turbine. These coatings did have some areas where rust from adjacent carbon steel stained the thermal sprayed coatings. In addition, these coatings had some areas where rust from the carbon steel substrate bled through the coating. There was no corrosion product bleed-through of the coatings applied over the stainless steel weld repair. A small portion of the Stellite 6® coating applied to the coated area on the vane showed an angular wear pattern. In all areas, the coating was still adhering well and showed no signs of separating from the steel. A photograph of the HVOF sprayed coatings on the vane is shown in Figure 16. The vanes are subjected to more aggressive cavita-

tion attack than the cone or the throat ring. Based on the good condition of the coatings in service, the coatings would be expected to continue to provide protection of the substrate. The coating conditions will continue to be monitored when outages and access permit. Such long-term monitoring of the thermal spray coating performance in the field must necessarily extend beyond the duration of this CPAR project.

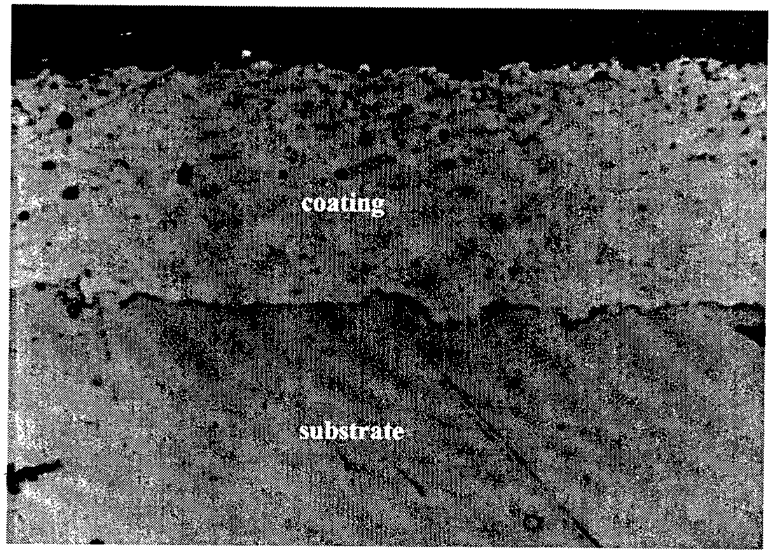


Figure 14. Micrograph of HVOF Stellite® 6 coating (20 mil) steel test panel showing decreasing porosity at the coating/substrate interface.

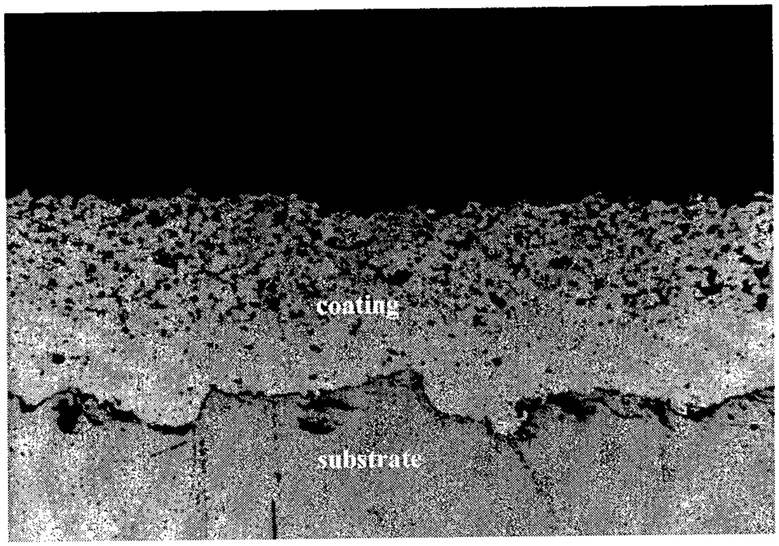


Figure 15. Micrograph of HVOF Tribaloy® T-400 coating (20 mil) on steel test panel showing good anchor profile at the coating/substrate interface.

Figure 16. HVOF coatings applied to the vane of a Francis pump/turbine at the Raccoon Mountain plant after 2175 hours of operations.

8 Other Applications

Pumps

Pumps are used for movement of liquid in both industrial and non-industrial processes. The centrifugal pump is the type most widely used in the chemical industry for transporting liquids. Centrifugal pumps are also widely used for pumping potable water, storm water, sanitary and industrial waste water, boiler feed, condenser circulation, and other applications. A centrifugal pump consists of an impeller rotating within a casing. The impeller comprises a number of blades mounted on a shaft that projects through the casing (Perry 1973).

Despite proper design and operation, cavitation, erosion, and corrosion can occur inside pumps and damage components. Thermal spray coatings may be applicable for the repair of the pump components, or they could be incorporated into the original pump design by the manufacturer. The use of thermal spray coatings such as Stellite® 6 applied by the HVOF process would be expected to improve the performance of pumps subjected to erosion and subsequent cavitation resulting from surface roughening.

A plasma spray coating (bond coat of Metco 447 molybdenum-based alloy and topcoat of Metco 103 Cr_2O_3) was applied in 1983 to the impellers of a 104 inch pump at the Corps of Engineers Graham Burke Pumping Station, Elaine, AK. This coating system has provided satisfactory service for 13 years. The use of improved coating systems, such as Stellite® 6 applied by the HVOF process, should provide equivalent or better performance. The pump at Graham Burke Pumping station will be overhauled in the summer of 1997. The overhaul will include removal of the impeller for weld repair and subsequent coating using the HVOF process of Stellite® 6. The specification for the repair of the storm water pump, prepared by the U.S. Army Engineer District Memphis, is attached at Appendix C.

Erosion

Three distinct types have been identified:

- solid particle erosion
- slurry erosion
- liquid droplet erosion.

Solid particle erosion is caused by the impingement of small solid particles against the surface. Slurry erosion, or liquid-solid erosion, is similar to solid particle erosion except that there are differences in the viscosity and density of the carrier medium (i.e., a gas in solid particle erosion versus a liquid in slurry erosion). Slurry erosion occurs at the surfaces impinged by solid particles in a liquid stream. The similarity to abrasion arises from the fact that particles are hydrodynamically forced against the surface. Liquid droplet erosion and cavitation have similar effects on a surface. Both produce a succession of shock waves that propagate into a surface. For this reason, materials that perform well under cavitation conditions will also resist liquid droplet erosion, and vice versa (Crook 1990).

As the data in Table 22 (Chapter 6) show, the thermal spray coatings prepared by HVOF performed better in slurry erosion wear testing than the uncoated cast carbon steel and stainless steel reference materials. The volume loss for Stellite® 6 coatings applied by the HVOF process was 5.33 mm^3/h, compared to the volume loss of 9.22 mm^3/h for 308 stainless steel and 19.70 mm^3/h for A572 carbon steel reference materials. A572 carbon steel is similar to the ASTM A516 carbon steel used by the Corps of Engineers for discharge rings, and similar to the ASTM 283 carbon steel used by the Corps for draft liner tubes. The change in a surface's roughness and geometry due to erosion can also result in the formation and collapse of cavitation vapor bubbles that result in surface damage. Minimizing erosion can minimize this resulting type of cavitation. Therefore, HVOF coatings may be considered for use in hydraulic equipment to protect against erosion wear and subsequent cavitation resulting from surface roughening.

Corrosion

According to the manufacturer, cobalt-based wear-resistant alloys such as Stellite® 6 and Tribaloy® T-400 possess superior corrosion resistance in aqueous environments compared to mild carbon steels, and similar corrosion resistance

compared to the stainless steels. Published results show that cobalt wear-resistant alloys undergo little attack in mine water, sea water, or boiler water at temperatures typical for those environments. After 2 years in sea water, wear-resistant cobalt alloys have shown a corrosion rate of about 0.0001 in. per year, with maximum pitting of 0.0007 in. (LaQue 1963). This rate is only 2 percent of the corrosion rate of mild steel in sea water, which occurs at about 0.005 in. per year (Fontana and Green 1978).

Stainless steel weld repair of mild carbon steel surfaces results in the formation of an interface between the mild carbon and the stainless steel. These two steels have different electrochemical potentials causing galvanic corrosion of the carbon steel. The damage to the carbon steel is usually repaired by welding more stainless steel. In some cases, entire throat rings have required stainless steel weld repair. Complete fusion welding of stainless steel overlay on the throat ring can produce thermal stresses on cooling. These thermal stresses cause the weld overlay and liner to pull away from the concrete support. The detached steel liner is subject to buckling and damage. In order to prevent this disbonding, anchors and grout are used, otherwise the steel liner would be overstressed. The thermal shrinkage stresses for thermal spray coatings are much lower than that from welding because the coatings are much thinner than the weld materials and thermal spray introduces less heat to the substrate than welding. Using thermal spray coatings on the entire throat ring or discharge tube liner would prevent the corrosion, erosion, and cavitation damage to the substrate and eliminate the need for extensive weld repair.

Measurements of the electrochemical potential of 304 stainless steel, ASTM A572 carbon steel and ASTM A36 carbon steel were made relative to a copper-copper sulfate reference electrode in tap water. The electrical conductivity of the tap water was 325 microsiemens (corresponding to a resistivity of 3075 ohm cm). The electrical potential differences between Stellite® 6 coated specimens and both ASTM A572 and A36 carbon steels in tap water were 0.25 volts—half the potential differences (0.5 volts) between 304 stainless steel and both ASTM A572 and A36 carbon steels. Therefore, Stellite® 6 would reduce the galvanic corrosion problem because of the smaller electrical potential difference. However if the interface corrosion between the stainless steel and carbon steel is shifted to the Stellite 6-carbon steel interface, then complete coverage by thermal spray coatings may be required.

Seal Coats

The use of an organic seal coat on top of the thermal spray coating may provide additional protection to the coating system. Previous results have shown that seal coats over HVOF sprayed coatings may improve the cavitation resistance of thermally sprayed coating (Baker 1994 and Lontz 1992). Although not investigated in this study, based on previous USACERL work, the use of seal coats may be considered by the operations engineer. For more information using polymer coating systems for cavitation applications, refer to Ruzga, Willis, and Kumar (1993).

The U.S. Bureau of Reclamation (USBR) tested a reinforced epoxy (Belzona Superglide®) and a polyurethane coating as seal coats for thermal spray coatings, Table 4 (Chapter 4). It was concluded that the reinforced epoxy (Belzona Superglide®) and polyurethane coatings added protection to thermal spray coatings when present. The reinforced epoxy (Belzona Superglide®) topcoats were found to be superior to polyurethane topcoats (Baker 1994). However, organic topcoats may produce toxic fumes when subsequent weld repair is performed on the coated area, which would require the use of additional personal protection equipment by the welding technician.

Certain fiber-reinforced glass ceramic coatings called CERHAB can be flame sprayed. These have been shown to have significantly higher cavitation resistance than Belzona Superglide® reinforced epoxy (Ruzga, Willis, and Kumar 1993). However, thermal annealing of field-applied CERHAB coatings maybe required.

9 Cost Analysis

Hydroelectric Turbines

Areas of medium and severe cavitation in hydroelectric turbines will require the removal of damaged materials and weld repair of the areas with stainless steel. The cost of weld repairs of cavitation on a hydroelectric turbine was determined for the Corps of Engineers Little Goose Dam on the Snake River in Washington (Ruzga 1993). Updating the cost to 1996 dollars, assuming a 4 percent per year cost increase, the total current cost of cavitation repair by welding would be about $561 per sq ft (Table 26).

Table 26. Weld repair costs at Little Goose Dam (Ruzga 1993)

Item	Cost per sq ft
Materials	$115
Labor	$384
Total Cost 1993	$499
4% per year cost increase for 3 years	$62
Total Cost (1996 $)	$561

Using HVOF, the surface (whether weld repaired or as-found) would be blasted with abrasive grit to remove corrosion product and to smooth out the erosion and corrosion pits. The HVOF process would provide a 0.020 in. coating that follows the resulting surface profile of the abrasive blasted substrate with a surface finish of 300 microinches R_a. The as-sprayed coating would be the finished surface, requiring no grinding or other additional work.

The cost analysis summarized in Table 27 showed that the cost of applying a 0.020 in. cavitation-resistant Stellite® 6 or Tribaloy® T-400 coating to a hydroelectric turbine would be $187 per sq ft using the HVOF process. This estimate does not include any costs associated with repairing the damaged area and bringing it up to contour by fusion welding prior to thermal spraying.

Table 27. Cost estimate for HVOF application of Stellite® 6.	
Total Area	400 sq ft
Coating Thickness	0.020 in.
Material Cost	$50/lb
Coating Spray Rate	10 lb/h
Total Repair Estimate	**$75,000**
Materials (Metal Powder, Blast Grit, Gases, Parts)	66%
Labor (application of materials)	33%
Cost per sqare foot	**$187 per sq ft**

As noted in Chapter 7, repairs required as a result of direct cavitation damage should be performed using a fusible material by a welding process. The cost analysis showed that the spray method of surface repair costs about one-third the cost of welding. With this in mind, one should stay informed about advances in this technology, as one day a material and process may be developed that will perform better than carbon steel in cavitation environments. However, Stellite® 6 coatings applied by the HVOF should be considered for the mitigation of erosion and the resulting cavitation due to surface roughening. Stellite® 6 coatings should also be considered for the prevention of dissimilar metal galvanic corrosion in water.

Pumps

The cost of repairing erosion damage on a centrifugal pump in the field by welding stainless steel was determined, and is itemized in Table 28. The estimate was based on a 4 ft diameter pump with the outer 1 foot of the impeller blades requiring repair. American Welding Society guidance was used to estimate the costs (AWS 1985).

Table 28. Cost estimate for weld application of stainless steel to a centrifugal pump in the field.

	Time	Cost
Preparation	4.0 hrs	$400
Welding	12.0 hrs	$1800
Cost of Materials		$375
Total		$2575
Total + Profit (10%)		$2833
Cost per sqare foot		**$258 per sq ft**

The cost estimate for the same pump using the HVOF process to apply Stellite® 6 is $109 per square foot (Table 29). The cost of comparable weld repair of a pump was estimated to be $258 per square foot.

Table 29 Cost estimate for HVOF application of Stellite® 6 to a centrifugal pump in the field.

	Time	Cost
Preparation	2.4 hrs	$150
Grit Blast	1.4 hrs	$150
Thermal Spray	4.0 hrs	$360
Cost of Materials		$425
Total		$1471
Total + Profit (10%)		**$1618**
Cost per sqare foot		**$109 per sq ft**

The cost of repairing a pump using HVOF thermal spray coatings was estimated to be less than one half the price of conventional weld repair. Therefore, the use of thermal spray coatings, such as Stellite® 6 applied by the HVOF process, should be considered for the repair of pumps subjected to erosion and subsequent cavitation caused by surface roughening.

10 Conclusions, Recommendations, and Commercialization

Conclusions

The thermal spray coatings deposited by the high velocity oxyfuel (HVOF) process and tested exhibited lower cavitation wear rates than the thermal spray coatings deposited by the plasma spray process, as determined by laboratory testing using the cavitating jet test apparatus.

Of the 21 thermal spray coatings tested in the laboratory using the cavitating jet apparatus, the lowest cavitation rate was for Stellite® 6 as applied by the HVOF thermal spray process. The cavitation rate of Stellite® 6 was 11.7 mg/h, while the corresponding cavitation rate for 308 stainless steel weld metal was 3.2 mg/h.

The field applicability of Stellite® 6 thermal spray coatings deposited by the HVOF process was successfully demonstrated on a hydroelectric pump/turbine at the TVA's Raccoon Mountain plant near Chattanooga, TN. Thermal spray coatings were applied to stainless steel weld-repaired substrates and carbon steel substrates.

The cavitation rates of advanced weld metal overlays, such as NOREM®, D-CAV®, CaviTec®, and Hydroloy® 914, ranged from 1.0 to 2.6 mg/h, which were lower than the corresponding cavitation rate for standard 308 stainless steel weld metal (3.2 mg/h).

In slurry erosion wear testing, the volume loss for Stellite® 6 coatings deposited by the HVOF process was 5.33 mm^3/h, less than half the volume loss of 11.17 mm^3/h for 304 stainless steel. The corresponding loss for ASTM A572 carbon steel was 19.70 mm^3/h.

The electrical potential differences between Stellite® 6 coated specimens and both ASTM A572 and A36 carbon steels in tap water were 0.25 volts, half the

potential difference between 304 stainless steel and mild carbon steel (i.e., 0.50 volts).

Stellite® 6 coatings deposited by the HVOF process over surfaces having dissimilar metals (i.e., stainless steel weld repair adjacent to the mild steel base metal) will mitigate the corrosion activity at the dissimilar metal boundary because of its superior corrosion resistance as compared to the carbon steel substrate material.

The cost of applying Stellite® 6 coatings to a hydroelectric turbine in the field, after the damaged surface was weld repaired, was determined to be $187 per sq ft. Weld repair, by contrast, costs three times as much.

The cost of applying Stellite® 6 using the HVOF process to a 4 ft diameter storm water pump for the mitigation of erosion and subsequent cavitation was estimated to be $109 per sq ft as compared to $258 per sq ft for weld repair.

The current state of the art in thermal spray processes and materials cannot provide a coating that is much better in resisting cavitation damage than a carbon steel material. Therefore, it is concluded that repairs required as a result of direct cavitation damage should be performed using a fusible material by a welding process.

This work has identified and developed a thermal spray coating material and process that will protect hydraulic turbine and pump water passages from damage due to erosion, cavitation resulting from erosion, and dissimilar metal corrosion damage.

Recommendations

Stellite® 6 deposited by the HVOF process should be considered for the repair of damage resulting from erosion and subsequent cavitation caused by surface roughening. Stellite® 6 coatings should also be considered for the mitigation of galvanic corrosion associated with contact between dissimilar metals in water.

Repairs required as a result of direct cavitation damage should be performed using a fusible material by a welding process. For severe cavitation, defined as more than 1/8 inch damage to austenitic stainless steel (308 SS) in 6 months or less, welding advanced iron-based alloys such as NOREM®, D-CAV®, CaviTec®

and Hydroloy® 914 should be considered for use due to their superior cavitation resistance.

Stellite® 6 coatings deposited by the HVOF process should be considered for application to turbine throat rings and draft tube liners in order to prevent erosion and corrosion to the carbon steel substrate and to avoid the thermal stresses associated with fusion welding of stainless steel. This application will also minimize galvanic corrosion caused by the potential difference between the carbon steel and conventional stainless steel weld materials. However, if the interface corrosion between the stainless steel and mild carbon steel is shifted to the Stellite® 6 / carbon steel interface, then complete coverage by the thermal spray coating may be required. Small-scale testing prior to full-scale utilization is recommended to confirm suitability for the specific field conditions.

The use of thermal spray coatings, such as Stellite® 6 applied by the HVOF process, should be considered for the repair of pumps subjected to erosion and subsequent cavitation caused by surface roughening.

All metal repair processes, including the welding and thermal spray coating processes described in this report, require that appropriate safety precautions be taken. The safety precautions specified for thermal spray processing are detailed in the proposed Corps of Engineers Civil Works Guide Specification (CWGS) attached at Appendix D. Additional relevant safety requirements are described in CWGS 05036, *Metallizing: Hydraulic Structures* (1992); Engineer Manual (EM) 3850101, *Safety and Health Requirements Manual* (3 September 1996); the *Welding Handbook* (American Welding Society 1994), Code of Federal Regulations (CFR) Title 29, Part 1910, *Occupational and Health Standards*; and 29 CFR 1926, *Safety and Health Regulations for Construction.*

Commercialization and Technology Transfer

Flame Spray Industries has begun a marketing initiative to promote cavitation- and erosion-resistant coatings in the hydroelectric and electric generation markets. The plan being pursued is to market to public utility districts in the Pacific Northwest and private utility companies nationally, as well as to TVA and USACE facilities for the onsite repair of hydroelectric turbines and pumps. The specific components targeted for rebuild and protection coatings with the Stellite® 6 are hydroelectric turbine draft tube liners and pumps. Other potential coating applications for erosion and corrosion prevention include

commercial pump components, toroidal rings of the cooling components of nuclear plants, and the water boxes of heat exchangers.

Flame Spray Industries will market the process through National Thermospray, Inc., Cypress, TX, and other companies with experience applying thermal spray coatings in the field. National Thermospray, Inc., has extensive experience in applying nickel and cobalt superalloys in the field for applications to the petrochemical industry. The majority of their current work is in confined spaces. The company is capable of preparing and applying coatings to interior surfaces 5 to 20 ft in diameter with thermal spray equipment that can be passed through a 20 in. hatch. As part of their business plan National Thermospray has acquired additional equipment to increase their field application capabilities. The process can be obtained by contacting Flame Spray Industries, Fort Washington, NY, or National Thermospray, Inc., Cypress, TX.

Flame Spray Industry will also market the use of HVOF coatings to original equipment manufacturers of pumps for the control of erosion. Preliminary discussions have been conducted with a major pump manufacturer who expressed interest in replacing currently used spray and fuse coatings with HVOF coatings in pumps. Pumps for the transport of liquid slurry in pulp and paper plants is a market segment that will be targeted for the use of HVOF coatings. The field repair of fuel and water pumps for public and private utility electrical generating plants is another market segment that will be targeted. The repair of fan impellers for the movement of air in coal-fired power plants, which are subjected to wear and abrasion, also will be targeted.

A proposed draft Civil Works Guide Specification, prepared by U.S. Army Engineer District Portland, is included in Appendix D. The technology transfer effort also included the preparation and distribution of a technical summary of this report's findings by personnel of the Hydroelectric Design Center (HDC), North Pacific Division, U.S. Army Corps of Engineers (Appendix E). The manager of the engineering laboratory, Tennessee Valley Authority, will promote the use of these materials throughout the TVA.

The American Society of Testing and Materials (ASTM) has established Committee B08, "Metallic and Inorganic Coatings," and subcommittee B08.14, "Thermally Deposited Coatings." Current ASTM task groups include B08.14.05, "Standards for Thermal Spray," and B08.14.07, "Thermal Spray Equipment." The CPAR partner's Principal Investigator at the State University of New York at Stony Brook (SUNY) officially requested that ASTM develop an industrial standard for HVOF coatings for cavitation and erosion applications.

The results of this project are scheduled for presentation at the 1997 National Thermal Spray Conference of the American Society of Metals International, and will be published in the conference proceedings.

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Appendix A: Results of Ultrasonic Cavitation Screening

	60 Minutes			120 Minutes		
Material	Weight Loss (mg)	Standard Deviation	Percent Standard Deviation	Weight Loss (mg)	Standard Deviation	Percent Standard Deviation
Steel Reference						
SAE 1020	2.1			6.7		
Cold Rolled	2.5			5.9		
	2.8			7.2		
avg.	2.5	0.4	14.7	6.6	0.7	9.9
SS-308	3.4			9.8		
Welded	4.5			10.8		
	3.9			12.8		
avg.	3.9	0.6	14.0	11.1	1.5	13.7
HVOF						
Nistelle D	169			220		
HVOF	180			256		
	198			267		
avg.	182.33	14.6	8.0	247.67	24.6	9.9
Tribaloy 700	110			169		
HVOF	135			180		
	137			198		
avg.	127.33	11.7	11.8	182.33	14.6	8.0
SS type 316	135			178		
HVOF	145			190		
	156			215		
avg.	145.33	10.5	7.2	194.33	18.9	9.7
Ni-5% Al alloy	124			156		
HVOF	145			166		
	154			179		
avg.	141.00	15.4	10.9	167.00	11.5	6.9

NOREM® HVOF	21			35		
	24			37		
	27			39		
avg.	24.00	3.2	12.5	37.00	2.0	5.4
Metco HVOF	38			89		
71 VF-NS-1	41			98		
	42			102		
avg.	40.33	2.1	14.8	96.33	3.7	7.8
Tribaloy® T-400	30.1			50.4		
HVOF	40.6			48.3		
	35.6			43.2		
avg.	35.43	5.3	14.8	47.30	3.7	7.8
Tribaloy® T-800 (.040 in.)	59.6			110.5		
HVOF	67.3			135.2		
	62.9			89.3		
avg.	63.27	3.9	6.1	111.67	23.0	20.6
Tribaloy® T-800 (.020 in.)	23.1			29.7		
HVOF	26.3			31.6		
	19.2			26.9		
avg.	22.87	3.6	15.5	29.40	2.4	8.0
Stellite®-6	4			6.5		
HVOF	3.8			5.9		
	4.3			6.9		
avg.	4.03	0.3	6.2	6.43	0.5	7.8
Sylvania	34			104		
Osram 158	50			115		
HVOF	59			138		
avg.	47.67	12.7	26.6	119.00	17.3	14.6
Plasma Spray						
SS 316 Plasma	59			89		
	67			102		
	78			108		
avg.	68.00	9.5	14.0	99.67	9.7	9.7
NOREM® Plasma	29			45		
	35			47		
	42			53		

avg.	35.33	6.5	18.4	48.33	4.2	8.6
NiCrBSi	29			45		
Plasma	35			47		
	42			53		
avg.	35.33	6.5	18.4	48.33	4.2	8.6
SS 430	84			135		
Plasma	98			146		
	105			158		
avg.	95.67	10.7	11.2	146.33	11.5	7.9
Metco 71 VF-NS-1	55			437		
Plasma	68			119		
	69			133		
avg.	64.00	7.8	12.2	146.33	17.9	78.2
Tribaloy® T-800	59.3			92.3		
Plasma	65			95.2		
	70.1			105.4		
avg.	64.80	5.4	8.3	97.63	6.9	7.0
Tribaloy® T-400	61.8			102.9		
Plasma	74.1			132.4		
	57.6			100.7		
	48.0			84.60		
avg.	60.38	10.8	17.9	105.15	19.9	18.9
Stellite® 6	19.3			36.2		
Plasma	21			39.1		
	17.4			31.1		
avg.	19.2	1.8	9.4	35.5	4.1	11.7
Combustion Cavitation Materials						
Al-Zn	135		159	211		
Combustion	148			230		
	159			241		
avg.	147.33	12.0	8.2	227.33	15.2	6.7
Two-Wire Arc Cavitation Materials						
430 SS	110			145		
Two Wire Arc	115			152		
	135			168		
avg.	120.00	13.2	8.2	155.00	11.8	7.6

CaviTec®	98			158		
Two Wire Arc	120			172		
	134			188		
avg.	117.33	18.1	15.5	172.67	15.0	8.7
316 SS	106			185		
Two Wire Arc	126			193		
	135			214		
avg.	122.33	14.8	12.1	197.33	15.0	7.6

Appendix B: Manufacturer's Data for Stellite® 6

Provided by Stellite Coating Co., Goshen, IN

Chemical Composition:

Cr	C	W	Ni	Fe	Co
29	1.1	4	3	3	Bal.

Hardness R_c: 41-44

Hot Hardness DPH 300:

800°F	1000°F	1200°F	1400°F
350	295	265	180

Metal to Metal Wear Resistance (ASTM G-77):

Load Lb.	90	150	210	300
Volume Loss mm^2	1.03	2.57	9.54	18.8

Abrasion Resistance, volume loss (ASTM G-65): 64 mm^3

Impact Energy: 23 Joules

Threshold Galling Stress: Against 1020 steel: 25 Kpsi
Against Stellite 6: 50 Kpsi

Corrosion Resistance:

Medium	30% HCOOH, 150°F	30% CH_3COOH, Boiling	5% H_2SO_4, 150°F	65% HNO_3, 150°F
Corr. Rate (mpy)	<5	<5	<5	>50

Appendix C: Specification For Repair and Thermal Spray Coating of a Storm Water Pump

Prepared by

U.S. Army Corps of Engineers

Memphis District

Tennessee

WORK STATEMENT/DESCRIPTION/SPECIFICATIONS

A-1. GENERAL

A1.1 Scope of Work. Work under this contract consists of rebuilding the main storm water pumps at the Graham Burke Pumping Plant near Mellwood, Arkansas.

A-1.2 Responsibility of the Contractor. The Contractor shall be responsible for the following:

(a) Furnishing new components, as necessary, to rebuild for the existing storm water pumps. These components shall be equivalent to the originals as shown on the drawings. The new components, as a minimum, shall include the following:

Item	FBM Number	Qty/Pump	Name
23	WHD98A	2	Bearing Half
22	-----	4	3/4 x 3/4 x 36-15/16 Packing (Asbestos Substitute)
25	CP6099F	6	Garlock Split Seals
26	WZB118A	6	Closure Plate Half
28	WHD14A	2	Upper Sleeve Half (Plain) (Same as Lower Sleeve Half)
27	WHD14B	1	Upper Sleeve Half (Keyed)
41	WHD14C	1	Lower Sleeve Half (Keyed)
43	WHD98B	2	Bearing Half
51	WHD3A	1	Prop Housing (New SST Plate)
--		As Required	New Stainless Steel Bolts

(b) Furnishing special tools and labor required for field machining of the bearing shell seats in the main pump bodies, for both upper and lower bearing shells. The machining accuracy shall be sufficient to insure that the bearing shells will fit into the seats, with concentricity maintained according to original factory specifications. After the seats are satisfactorily machined, the two upper bearing housing halves (WHD5B) and two lower bearing housing halves (WHD5A) shall be built up with weld and then machined to custom fit the registers. New or oversize bolt holes shall be drilled and tapped, for at least Pump Nos. 2 and 3. Part Numbers WHD5B and WHD5A may be replaced with new parts at the Contractor's option. Regardless of the option chosen, the Contractor shall measure and record the outside diameters of the replacement bearing housing halves for future reference.

(c) Verification that the pump shafts are straight within manufacturer's tolerances.

(d) Shop priming and painting of all steel components (except impellers) that are supplied under this contract.

(e) A cast shall be made of at least one of the impellers, to assist in manufacture of a new impeller at a later date. This casting of the impeller shape is to become property of the Government, and shall be delivered to the Graham Burke Pumping Plant at the conclusion of this Contract.

(f) Removal, inspection, rehabilitation, coating, and reinstallation of the pump impellers (WHD1A). The impellers presently have pitting on the faces, and metal is eroded away from the tips. This use related wear and tear has resulted in increased cavitation on the faces, and recirculation of water around the propeller tips. Both of these conditions result in loss of efficiency, and the repairs are to be made such that the original efficiency is regained. The impeller **tips** are to be built up with stainless steel weld overlay and then shop machined to restore the original O.D. (Outside Diameter), with 125 RMS finish on the tips. Pitting and erosion damage on the **face** of the impellers shall be repaired with mild steel overlay, and then ground down to a smooth face. The faces of the impeller blades shall be blast profiled to 300 RMS for secure adhesion of the cavitation resistant coating. The impellers are to be balanced after repairs to manufacturer's recommended tolerances for new pumps.[1]

[81] Cavitation resistance, in order of effectiveness, is as follows:

(g) Rehabilitation or replacement of the propeller housings (WHD3A), in way of the impellers. There is presently erosion of the housings where the impeller tips sweep past as the pumps operate. The insides of the propeller housings shall be rehabilitated with rolled stainless steel plate as a complete replacement for the original mild steel rolled plate, and the end flanges may be reused or replaced with new ones at the option of the Contractor.

(h) Services of a Government approved, factory trained and qualified service engineer that has a minimum of two years experience rebuilding props of a size comparable to the size and complexity of the units used on the Graham Burke Pumping Plant. The service engineer is to supervise all pump dismantling and reassembly operations. The Government will supply all labor and standard equipment at the project site to remove all pump components, and for reassembly once all new and rehabilitated parts have been brought back to the plant for reinstallation.

(I) Warranty of the impellers, bearings, shaft sleeves, bearing housings, Contractor- applied paint coatings, and seals against defects for a period of two years or two hundred pumping hours, whichever comes first.

A-1.3 Castings. All new castings that may be furnished under this Contract shall be inspected with a fluorescent or dye penetrant and a developer to reveal cracks and discontinuities. The Government reserves the right to perform additional casting inspections, using X-ray and/or ultrasonic methods, at its own expense.

A-1.4 Tolerances.

---

(1) Anticipated high bond strength coating over mild steel on impeller face (highest)

(2) Stainless steel, no coating, face or edge

(3) Anticipated high bond strength coating over stainless steel on face

(4) Mild steel, no coating

(5) Anticipated high bond strength coating over mild steel on edge (this is lower due to edge effects)

(6) Anticipated high bond strength coating over stainless steel on edge (lowest)

Anticipated coating is approximately .020" (0.5 mm) thick, for optimal performance. .040" (1.0 mm) thick does not perform nearly as well. Likewise, high hardness coatings are best for erosive service (sand), but high bond strength coatings are best for cavitating service (clean or muddy water free of sand) seen at Graham Burke.

A-1.4.1. General. All tolerances not noted herein shall be equivalent to original manufacturer's tolerances. The Government will examine all submittals to insure that, in its judgement, observed tolerances used by the Contractor under this contract will insure parts equal or superior to the original parts as supplied with the storm water pumps at the Graham Burke Pumping Plant.

A-1.4.2. Dynamic balancing. In addition to dimensional measurement, each impeller shall be assembled into a fixture for dynamic balancing. In addition, hydraulic imbalance as a result of shape differences shall not exceed original factory specifications when pumping at 600 CFS.

A-1.4.3. Dimensional tolerances. The fit of the completed impellers, installed in the pumps, shall work out to not have any interference, nor have a gap of larger than 0.090 inches between the periphery of any of the blades and the inner surface of the pump bowls. The size, dimensions and concentricity of the blade hubs as assembled into the lower pump hubs shall also be according to manufacturer's recommendations for the seals. Fillet and radius tolerances shall be maintained such that no cracks form in the material used, regardless of the number of pump starts and running hours.

A-1.4.4. Surface finishes. No areas of pitting or honeycombing are permitted on the outer shape of the impeller blades nor the inner surface of the lower pump bowls as these will allow cavitation to occur easily. Except as otherwise noted in these specifications or the drawings, the as machined surfaces shall have a surface finish of 125 RMS maximum.

A-1.5 Disassembly.. Each pump shall be dismantled in the field for a thorough inspection for excessive wear, fretting, and other corrosion caused by operation without proper lubrication. The Contractor shall give five days notice to the Contracting Officer so that he can arrange to have a Government representative observe the condition of the pumps as they are dismantled. The Contractor can then make recommendations to address conditions that may be revealed by this disassembly to the Government representative so that proper remedial action can be expeditiously be planned for.

A-1.6 Pump Impeller Repairs and Coating.. Each impeller (WHD1A) shall be shop coated with cavitation resistant coating, with high bond strength being of primary importance. This will require that the impellers be completely cleaned, dried, and profile blasted on the working faces to 300 RMS. The coating shall be Stellite 6 applied using the High Velocity Oxygen Fuel Process to a thickness of 0.020 inches [0.5 mm].

A-2. PRESENCE OF GOVERNMENT INSPECTOR

Unless waived in writing, all inspections shall be made in the presence of a Government Inspector and four copies of all inspection results thereof shall be furnished to the Contracting Officer. Where the presence of a Government Inspector is waived, four certified copies of test reports shall be furnished to the Contracting Officer.

A-3. COSTS

Except as provided elsewhere in the specifications, costs of all tests, exclusive of the expense of the Government representative shall be borne by the Contractor, and no separate payment will be made therefor.

A-4. SUBMITTALS

A-4.1 Shop Drawings. Shop drawings shall be submitted for approval in accordance with the Contract Clauses. Drawings shall include catalog cuts, templates, fabrication and assembly details, and type, grade, and class of materials, as appropriate. The Contractor shall not start the work specified herein until approval of the shop drawings has been received in writing from the Government.

A-4.2. Experience and Qualifications of Service Engineer(s). A resume of each service engineer the Contractor proposes to employ for this contract shall be provided. The resumes shall show a high level of competence can be expected in discharging the duties described in 1.2 (h).

SECTION B - PRESERVATION/PACKAGING/PACKING

B-1. Preservation packaging, and packing for shipment of all items shall be in accordance with commercial practice and adequate for acceptance by common carrier and safe transportation. Each impeller shall be individually mounted on a skid of ample size to facilitate loading and unloading. Bracing shall be used as necessary to prevent distortion of large cast or machined parts. Small parts shall be wrapped and boxed. Each pump item shall be protectively processed for short term indoor storage. The impeller blade casting(s) shall be processed for long term indoor storage without climate control.

B-2. The Contractor shall furnish for approval, in accordance with the requirements of Section 1.2, a complete description of the processing method or

methods he intends to use, including instruction for maintaining the protection during the storage periods in accordance with Section B-1.

B-3. The Contractor shall prepare and load all components for shipment, whether from the Graham Burke Pumping Plant to the Contractor's facility or from the Contractor's facility to the Graham Burke Pumping Plant. This preparation shall be in such a manner as to protect them from damage in transit, and the Contractor shall be responsible for and make good any and all damage until all deliveries are completed. Weatherproof covers shall be provided to protect the components during shipment. Machined surfaces shall be secured to avoid damage during loading, transit, or unloading. Any eye-bolts, special slings, strongbacks, skidding attachments, or other devices necessary for loading or unloading the equipment at the Graham Burke Pumping Plant or at the Contractor's facility shall be furnished at the destination and shall become the property of the Government.

SECTION C - INSPECTIONS

C-1.1 General. All work shall be subject to inspection by the Contracting Officer or his duly authorized representative as set forth in Clause 47 of the Contract Clauses. The Contractor shall notify the Contracting Officer, in writing, at least five calendar days in advance of the date that any tests or inspections are to be conducted.

C-1.2 Inspection Requirements.

C-1.2.1 Quality Control System. The Contractor shall submit to the Contracting Officer for approval the quality control system he proposes to use, before commencement of work under this contract. Complete facilities for checking the dimensional accuracy of the parts and for assurance of conformity of material requirements shall be furnished, maintained, and operated by the Contractor and/or his subcontractors. These facilities shall be separate from the production facilities to the extent that the parts are checked for compliance with the plans and specifications rather than tooling or production procedures. Certification by ISO 9000 will be taken as evidence the inspection organization and program to be applied during the course of this contract is satisfactory.

C-1.2.2 Tests. In addition to the tests for qualification and control of procedures set forth in the specification as well as inspections determined by the Contractor under the approved quality control plan, the following approvals and tests shall be made on the spare parts.

(1) Impeller Casting(s). Within 60 calendar days from the date of receipt of the first impeller blade at the Contractor's facility, the Contractor shall make available to the Contracting Officer for inspection the casting(s) of the impeller blade shape. After approval and verification that this casting(s) is fit for future manufacture of matching impellers, this casting(s) shall be packaged and delivered to the Government in accordance with Section D.

(2) Parts Inspection. The Contracting Officer shall have the right to send his authorized representative to the Contractor's facility to test and inspect the reworked parts. Inspections and tests may include hardness and other non destructive tests of mild steel and stainless steel weld overlays, visual verification of pump impeller repairs, review of stainless steel certification, verification of bronze bearing material, and dimensional checks.

(3) The Contractor may, at his option and expense, observe the above described testing. The Contractor shall notify the Contracting Officer if he intends to observe this testing.

C-2 ACCEPTANCE. No material or equipment shall be shipped until after it has been inspected and tentatively accepted for shipment by the Contracting Officer or his authorized representative, or unless inspection of the equipment has been waived in writing. Final inspection and acceptance will be at destination.

SECTION D - DELIVERIES OR PERFORMANCE.

D-1. COMMENCEMENT AND PERFORMANCE

Within 10 days of contract award, the Contractor shall submit a proposed production schedule for Contracting Officer approval. Approval by the Contracting Officer of the schedule is necessary to begin work. Contractor shall make delivery of the parts within the time schedule specified in paragraph D-2 below.

D-2. DELIVERY SCHEDULE

One (1) pump unit shall be reworked in FY 1997, one (1) pump unit shall be reworked in FY 1997, and one (1) pump unit shall be reworked in FY 1999. Total turnaround time from shipping of existing components to receipt at the Graham Burke Pumping Plant of reworked pump components shall not exceed 60 days for each pump unit. The Contracting Officer shall give five working days

notice to the Contractor for pickup of existing components. The Contractor shall give the Contracting Officer five working days notice before expected deliveries of reworked pump components at the Graham Burke Pumping Plant. New special tooling and fixtures (if any) such as patterns, jigs, and dynamic balancing fixture shall also be delivered to the Government at the conclusion of this Contract.

The Contractor shall submit proposed production and shipping schedules, together with contingency plans in case of interruption of work due to high water conditions.

D-4. DELIVERY DESTINATION

All materials and equipment to be picked up and delivered by the Contractor shall be delivered f.o.b. destination to the Memphis District, Graham Burke Pumping Plant. The Contractor shall notify the Contracting Officer at least five days in advance of any shipment to be made under this contract.

Appendix D: Proposed Draft CWGS for Thermal Spray Coating of Hydroelectric Turbine Components

Prepared by

U.S. Army Corps of Engineers,

Portland District

Oregon

PROPOSED DRAFT GUIDE SPECIFICATION:

Thermal Spray Coating of Hydroelectric Turbine Components

1. BACKGROUND: Cavitation and erosion damage to hydroelectric turbines is a significant generation loss. Eroded blade and throat ring surfaces reduces turbine efficiency; it also increase waters turbulence, which increases mortality of young fish passing through the unit.

2. OBJECTIVE: The objective is to coat affected turbine surfaces with a non-fusion, thermal-sprayed erosion and cavitation-erosion-resistant coating. The coating will be applied with the High Velocity Oxyfuel (HVOF) spray process.

3. GENERAL

3.1 REFERENCES
The publications listed below form a part of this specification to the extent referenced. The publications are referred to in the text by basic designation only. In all listed references, the most current version applies.

3.1.1 AMERICAN CONFERENCE OF GOVERNMENTAL INDUSTRIAL HYGIENISTS (ACGIH)

ACGIH-02 Threshold Limit Values for Biological Agents and Biological Exposure Indices

3.1. 2 AMERICAN NATIONAL STANDARDS INSTITUTE (ANSI)

ANSI Z49.1 Safety in Welding and Cutting

ANSI Z87.1 Occupational and Educational Eye and Face Protection

ANSI Z88.2 Practices for Respiratory Protection

ANSI Z89.1 Protective Headwear for Industrial Workers

3. 1. 3 AMERICAN SOCIETY FOR TESTING AND MATERIALS (ASTM)

ASTM C 633 Adhesion or Cohesive Strength of Flame-SprayedCoatings

ASTM D 3740 Practice for Minimum Requirements for Agencies Engaged in Testing and/or Inspection of Soil or Rock as Used in Engineering Design and Construction

ASTM D 3951 Commercial Packaging

ASTM E-329 Specification for Agencies Engaged in the Testing and/or Evaluation of Materials Used in Construction

ASTM D 4417 Field Measurement of Surface Profile of Blast Cleaned Steel

3. 1. 4 CODE OF FEDERAL REGULATIONS (CFR)

CFR 29 Part 1910 Occupational Safety and Health Standards

CFR 30 Part 11 Respiratory Protective Devices; Tests for Permissibility; Fees

3. 1. 5 COMPRESSED GAS ASSOCIATION (CGA)

CGA G-7.1 Commodity Specification for Air

CGA P-1 Safe Handling of Compressed Gas in Containers

EM 385-1-1 U. S. Army Corps of Engineers Safety and Health Requirements Manual

3. 1. 6 FEDERAL STANDARDS (FED-STD)

FED-STD 151 Metals, Test Methods

3.1.7 MILITARY STANDARDS (MIL-STD)

MIL-STD 105 Sampling Procedures and Tables for Inspection by Attributes

3.1.8 NATIONAL FIRE PROTECTION ASSOCIATION (NFPA)

NFPA 70 National Electrical Code

3.1.9 STEEL STRUCTURES PAINTING COUNCIL (SSPC)

SSPC PA 2 Measurement of Dry Paint Thickness with Magnetic Gages

SSPC SP 6 White Metal Blast Cleaning

3.2 NOMENCLATURES

3.2 Metallizing: The term "metallizing" as used herein refers to any of several application methods for depositing thermal spray metal coatings.

3.2.2 Confined Space: A confined space is any space having limited openings for entry and exit, not intended for continuous occupancy and with unfavorable natural ventilation, which could contain or have produced dangerous concentrations of airborne contaminants or asphyxiants. Confined spaces may include, but are not limited to, storage tanks, holds of vessels, manholes, process vessels, bins, boilers, ventilation or exhaust ducts, sewers, underground utility vaults, tunnels, pipelines, trenches, vats, and open-top spaces more than 4 feet in depth such as pits, tubs, vaults, and vessels, or any place with limited ventilation.

3.2.3 Oxygen Deficient: When cited within this document, the term "oxygen deficient" shall apply to any atmosphere with an oxygen concentration of 19.5 percent or less.

3.2.4 Immediately Dangerous to Life or Health (IDLH): That concentration of oxygen, carbon dioxide, or other contaminant that will cause incapacitating illness or death within a short period of time.

3.3 SUBMITTALS

Government approval is required for submittals with "GA" designation; submittals having "FIO" designation are for information only.

3.3.1 SD-06 Instructions

3.3.1.1 Accident Prevention Plan; GA.

A written accident prevention plan that complies with requirements of EM385-1-1 Section 1, "Program Management," and Appendix A, "Minimum Basic Outline for Accident Prevention Plan". The Accident Prevention Plan shall be prepared by a qualified occupational safety and health professional who has a minimum of 3 years experience in safety and industrial hygiene. The Accident Prevention Plan shall address the following requirements as a minimum:

(1) Identification of Contractor personnel responsible for accident prevention.

(2) Methods Contractor proposes to coordinate the work of its subcontractors.

(3) Layout plans for temporary buildings, construction of buildings, use of heavy equipment, and other facilities.

(4) Plans for initial and continued safety training for each of the Contractor's employees and subcontractor's employees.

(5) Plans for traffic control and the marking of hazards to cover waterways, highways and roads, railroads, utilities, and other restricted areas.

(6) Plans for maintaining good housekeeping and safe access and egress at the jobsite.

(7) Plans for fire protection and other emergencies.

(8) Plans for onsite inspections by qualified safety and health personnel. Plans shall include safety inspections, industrial hygiene monitoring if required, records to be kept, and corrective actions to be taken.

(9) Plans for performing Activity Hazard Analysis for each major phase of work. The Activity Hazard Analysis shall include the sequence of work, specific hazards that may be encountered, and control measures to eliminate each hazard.

(10) Procedures for notifying the dam control room in the event of an emergency requiring an ambulance.

(11) Evacuation procedures for the entire crew and for injured individual

3.3.1.2 Confined Space Procedures; GA.

A written confined-space procedure in compliance with EM 385-1-1, Section 6, "Hazardous Substances, Agents and Environments," Subsection 06.I, "Confined Space," on Confined Spaces, as well as any applicable Federal and local laws.

3.3.1.3 Respiratory Protection Program; GA.

A written respiratory protection program as specified in 29CFR Part 1910, Section 134(b).

3.3.1.5 Air Sampling; GA.

Plans for conducting air sampling by qualified individuals for toxic contaminants if the Contractor uses wire or fluxes containing beryllium, cadmium, fluorine compounds, lead,

mercury, zinc or other metals, and solvents or other chemicals regulated by the Occupational Safety and Health Act (OSHA).

3.3.1.6 Ventilation Assessment; GA.

A written plan for ventilation assessments to be performed by a qualified person for all confined-space work, solvent cleaning, abrasive blasting, and metallizing operations.

3.3.1.7 Worker Hazard Communication Program; GA.

A written Hazard Communication Program as required by 29CFR Part 1910, Section 120. The written program shall describe how the hazard communication program is to be implemented, labels and other forms of warning, material safety data sheets, a chemical inventory, employee information and training, methods the employer will use to inform employees of hazards associated with nonroutine tasks and unlabeled pipelines, and the methods the employer will use to inform Government employees and subcontractors of chemical hazards.

3.3.2 SD-08 Statements

3.3.2.1 Medical Surveillance; FIO.

A written record of physical examinations provided to all employees who may be required to wear a respirator, who may be exposed to excessive noise levels, or who may be exposed to toxic contaminants. Documentation shall include statements signed by the examining physician for each employee that the exam included the minim requirements as described in the paragraph Medical Surveillance

3.3.2.2 Qualifications and Experience; GA.

A written Qualification and Experience statement signed and dated by the Contractor and the Qualified and Competent Person that the Contractor has selected to develop the required safety and health submittal items and who will act as the Contractor's onsite safety and health representative during the contract period, prior to submission of other required safety and health submittal items.

3.3.2.3. Safety Indoctrination Plan; GA.

Documentation of the safety indoctrination plan as described in EM 385-1-1.

3.3.3 Operating Procedures

3.3.3.1 Description of the Surface Preparation Procedure; GA

The Contracting Officer shall supply the Contractor with written surface preparation requirements. The Contractor shall use these surface preparation requirements and develop written procedures for the grit blast operation. The operation procedure shall describe the use of non-recycled grit to prevent contamination. It should describe procedures to ensure that the grit blasted surface will be free of moisture, oil and debris contamination including dust or grit particles settled on the surface. It should describe how the resulting surface finish will have an angular grit blasted surface with a minimum of 300 microinches Ra over a 0.100 inch travel with a waviness cut off of 0.030 inches. It should further describe how the grit blast media will be removed from the platform on a continual basis for weight reasons. It should also summarize how the weight of the grit, equipment and personnel on the platform at any time will not exceed the load rating of the platform. The procedure shall be submitted and approved by the Contracting
Officer.

3.3.3.2 Description of the Thermal Spray Procedure, GA

The Contracting Officer shall supply the Contractor with a written description of spray parameters. The Contractor shall use the spray parameters to develop written procedures for the spray operation. These shall include at minimum the spray procedure and allowable temperatures of the surface prior to, during and after thermal spray coating application. The written thermal spray procedure shall be submitted and approved by the Contracting Officer.

3.3.3.3 Written Inspection Procedures; GA

The Contractor shall develop written inspection procedures. The inspection procedure shall include thickness and hardness measurements. The Contractor shall describe the number and type of test panels that will be sprayed and tested during the spray application. The tests will include but are not limited to hardness and thickness testing. The Contractor shall delineate where the hardness test will be performed on-site such as in the Contractors vehicle or at the staging area. The hardness tester will be calibrated against a calibrated traceable source test block with three indentations prior to testing samples. The Contractor will describe the method and source of calibration for the micrometers and other thickness monitoring devices. The Contractor shall describe in full the procedure to prepare the test samples. The written inspection procedures shall be submitted and approved by the Contracting Officer.

3.3.4. SD-09 Reports

3.3.4.1. Thermal spray powder; GA.

A certified test report showing the results of the required tests made on the thermal spray powder and a statement that it meets all of the specification requirements.

3.3.5 SD-14 Samples

3.3.5.1 Sprayed Coating; GA.

Prior to the on-site efforts, the Contractor shall supply coatings applied to a minimum of 4 panels of 3 inches x 3 inches X 0.25 inch (7.6cm X 7.6 cm X .64 cm) steel plate. The steel plate shall have the same chemical composition as the work surface to be coated. The samples shall be blasted and sprayed using the approved written procedures, in the same approximate orientation as the work surfaces. At no cost to the Contractor, these panels will be tested by the government for hardness, as well as sectioned and metallographically examined.

3.4 MATERIAL SAFETY DATA SHEETS

The Contractor shall have at the work site Material Safety Data Sheets (MSDS) for all solvents, chemical mixtures, welding wire, fluxes, powders, or any other product required to have an MSDS as specified in 29CFR Part 1910, Section 120. Contractor shall make required MSDSs available to Government personnel who may be exposed to those chemicals.

3.5 SAFETY AND HEALTH PROVISIONS

3.5.1 General

3.5.1.1 All work performed under this contract shall comply with the applicable provisions of the Corps "Safety and Health Requirements Manual," EM 385-1-1, and clauses below.

3.5.1.2 Thermal Spray Operations: Airborne metal dusts, finely divided solids, or other particulate accumulations shall be treated as explosive materials. Proper ventilation, good housekeeping, and safe work practices shall be maintained to prevent the possibility of fire and explosion. Thermal spray equipment shall not be pointed at a person or flammable material. Thermal spraying shall not be done in areas where paper, wood, oily rags, or cleaning solvents are present. Conductive safety shoes shall be worn in any work area where explosion is a concern. During metallizing operations, including the preparation and finishing processes, employees shall wear protective coveralls or aprons, hand protection, eye protection, ear protection, and respiratory protection.

3.5.2 Safe Surface Preparation Procedures

3.5.2.1 Hoses, nozzles and controls shall be designed, operated and maintained in accordance with EM 385-1-1, Sections 6 and 20.

3.5.2.2 Abrasive Blasting Respirator

Abrasive blasting operators shall wear an Abrasive Blasting Respirator (ABR), which consists of a continuous-flow air line respirator constructed so that it will cover the worker's head, neck, and shoulders from rebounding abrasive. Respiratory equipment shall be approved by the National Institute for Occupational Safety and Health and/or Mine Safety and Health Administration (NIOSH/MSHA). Compressed air shall meet at least the requirements of the specification for Type 1 Grade D breathing air as described in CGA G-7.1.

3.5.2.3 Personal Protective Equipment

Blasting operators shall wear heavy canvas or leather gloves and apron or coveralls. Safety shoes shall be worn to protect against foot injury. Hearing protection shall be used during all blasting operations.

3.5.3 Cleaning With Compressed Air

Cleaning with compressed air is restricted to systems where the air pressure has been reduced to 30 psi or less. Cleaning operators shall wear safety goggles or face shield, hearing protection, and appropriate body covering. Individuals shall not use compressed air or pressurized gas to clean clothes, hands, hair, or other areas on or near their person. Individuals shall not point a compressed air hose at any part of their bodies or at any other person.

3.5.4 Cleaning With Solvents

MSDSs shall be consulted for specific solvent information and procedures in addition to those listed here. Flammable liquid with a closed-cup test flash point below 100 degrees F shall not be used for cleaning purposes. Sources of ignition shall not be permitted in the vicinity of solvent cleaning if there is any indication of combustible gas or vapor present. Special precautions shall be taken when metallizing materials that have been cleaned with hydrocarbon solvents. Specific measurements shall be made to ensure that such solvent vapors are not present during metallizing operations, especially in confined spaces. Representative air samples shall be collected from the breathing zone of workers involved in the cleaning process to determine the specific solvent vapor concentrations. Worker exposures shall be controlled to levels below the OSHA Permissible Exposure Limit as indicated in 29 CFR Part 1910, Section 1000, whichever is more stringent.

3.5.5 Electrical Shock Prevention

3.5.5.1 Electrical shock hazards shall be addressed by strict observance of paragraphs .269 and .147 of 29 CFR 1910. Contractor shall pay particular attention to the following:

(1) Ground protection for equipment and cords shall be present and in good condition.

(2) Electrical outlets in use shall have Ground Fault Circuit Interrupters (GFCI) in addition to appropriate overcurrent protection.

(3) Electrical circuit grounds and GFCI shall be tested before actual work begins.

(4) Switches and receptacles shall have proper covers.

(5) Damaged cords and equipment shall be immediately repaired or replaced.

6) Circuit breaker boxes shall be closed.

(7) Cords shall be approved for wet or damp locations. The cords shall be hard usage or extra hard usage as specified in NFPA 70. Cords shall not be spliced.

3.5.6 Respiratory Protection Program. The Contracting Officer or his representative will determine if Engineering controls are not feasible, or during the time they are being installed, the Contracting Officer's representative may permit use of appropriate certified respiratory equipment to protect the health of each employee who may be exposed to air contaminants. Respirators shall be provided by the employer when such equipment is necessary to protect the health of the employee. The employer shall provide the respirators which are applicable and suitable for the purpose intended. The employer shall be responsible for the establishment and maintenance of a respiratory protective program. The employer shall use the provided respiratory protection in accordance with instructions and training received.

3.5.6.1 Requirements for Minimal Acceptable Program

1) Written standard operating procedures governing the selection and use of respirators shall be established.
2) Respirators shall be selected on the basis of the hazards to which the worker is exposed.
3) The user shall be instructed and trained in the proper use of respirators and their limitations.
4) Respirators shall be assigned to individuals for their exclusive use.
5) Respirators shall be regularly cleaned and disinfected after each use.
6) Respirators shall be stored in a convenient, clean, and sanitary location.
7) Appropriate surveillance of work area conditions and degree of employee exposure or stress shall be maintained.

8) There shall be regular inspection and evaluation to determine the continued effectiveness of the program.
9) Persons should not be assigned to tasks requiring use of respirators unless it has been determined that they are physically able to perform the work and use the equipment. The local physician shall determine what health and physical conditions are pertinent.
10) Approved or accepted respirators shall be used when they are available. The respirator furnished shall provide adequate respiratory protection against the particular hazard for which it is designed in accordance with established Project standards and by competent authorities.
11)Air line couplings shall be incompatible with outlets for other gas systems to prevent inadvertent servicing of air line respirators with nonrespirable gases or oxygen.
12)Breathing gas containers shall be marked in accordance with American National Standard Method of Marking Portable Compressed Gas Containers.

3.5.6.2 Written Program: The Contractor shall establish and implement a written respiratory protection program that shall include instruction and training about respiratory hazards, hazard assessment, selection of proper respiratory equipment, instruction and training in proper use of equipment, inspection and maintenance of equipment, and medical surveillance. The written respiratory program shall take into account current and anticipated work conditions for each work area and shall be specific for each work area. See sample written program, at para. 3.5.6.10.

3.5.6.3 Administration: The Contractor shall designate a person qualified by appropriate training and/or experience to be responsible for the respiratory protection program and for conducting the required periodic evaluation of its effectiveness. Qualifications of the competent person and the program content shall be reviewed and approved by the Contracting Officer.

3.5.6.4 Medical Acceptability: Before a worker is permitted to wear or be fitted for a respirator, the Contractor shall obtain a written statement from a licensed physician that the use of a respirator in the course of employment will not be deleterious to the worker's health. The employee's physical status shall be reviewed and reported in writing by the physician annually or at any time the employee experiences difficulty while wearing a respirator. To ensure that the physician is adequately informed of the specific requirements of the examination, the Contractor shall provide the physician with information about conditions in each work area such as, but not limited to:
(1) The type of respirator to be used.

(2) Contaminants from which protection is sought.

(3) Job description of the respirator user, including how often and how long the respirator will be worn each day.

(4) Environmental stress that may be encountered, such as, but not limited to, work to be done from an elevated platform, confined-space work, excessive heat, and additional clothing that will be worn.

3.5.6.5 Fit Testing: The Contractor shall provide respirators, at no charge to the employee, that are effective in reducing the maximum exposure to below the permissible exposure limit. At least 3 facepiece sizes shall be available from which to choose. After selecting the respirator, the employee shall wear it for a familiarization period of 10 minutes or more before fit testing. Fit testing shall be accomplished with irritant smoke or isoamyl acetate according to procedures set forth in ANSI Z88.2. Respirator wearers shall not have beards and other facial hair (sideburns, long mustache, etc.). Employees with facial hair that may interfere with the respirator fit shall not be tested and shall not be issued a respirator or allowed to work in contaminated areas until clean shaven and fitted with a respirator.

3.5.6.6. Respirator Selection: The Contractor shall select appropriate respirators from among those currently approved and certified by NIOSH/MSHA under the provisions of CFR 30 Part 11 and 29CFR Part 1910, Section 134. The Contractor's qualified person shall review selected respirators and practices at least annually to ensure that they comply with current standards and approvals. The Contractor shall review the manufacturer's approval for each respirator that may be issued at the jobsite. Instructions shall be on or in the carton with each device. If the Contractor has unanswered questions, the equipment manufacturer or its representative should be consulted for an explanation and training.

3.5.6.7 Use of Air Purifying Respirators: (NOT FOR USE IN OXYGEN-DEFICIENT OR IDLH ATMOSPHERES). Employees wearing quarter- or half-mask air purifying respirators shall not be subjected to atmospheric concentrations of more than 10 times the PEL, TLV, or manufacturer's recommended limit for the contaminant, whichever is lowest. To ensure that contaminant concentrations in the work place do not exceed exposure limits for the respirator selected, the Contractor shall monitor the atmosphere of the work area frequently, as determined by the Contracting Officer or his representative. If test results indicate a concentration greater than 10 times the recommended limits and additional ventilation or other control is not possible, the exposed worker shall then be provided and fit tested with a respirator that provides a higher protection factor.

3.5.6.8. Use of Air Line Respirators: Components of an air line respirator from one manufacturer shall not be used on an air line respirator from another manufacturer. In addition, components of a specific model from the same manufacturer shall not be interchanged with components of other models of the same manufacturer unless they are certified by NIOSH/MSHA to be interchangeable.

(1) The Contractor shall follow the respirator manufacturer's instructions for air line respirators. Specific attention shall be given to operating pressure and approved length of air line hose.

(2) The minimum air flow for tight-fitting face pieces is 4 cubic feet per minute (cfm).
(3) The minimum air flow for air line hoods is 6 cfm.

(4) Compressed air from cylinders shall meet the requirements of Grade D breathing air as described in CGA G-7.1.

(5) The air intake for air compressors shall be located and constructed so that contaminated air is not drawn into the compressor. In-line sorbent and high-efficiency filters shall be in place to improve the quality of compressed breathing air. For oil-lubricated compressors, an in-line carbon monoxide detector shall continuously monitor the breathing air. A warning and alarm (20 ppm warning, 30 ppm alarm) shall be conveyed to the user. High-temperature warning and shutoff controls shall be installed on compressors that are used for supplying breathing air.

3.5.6.9. Self-Contained Breathing Apparatus (SCBA): Employees who are required to enter areas that are oxygen-deficient or where the toxic concentration is greater than 1000 times the PEL or TLV and/or is IDLH, or in which the concentration is unknown, shall wear a self-contained breathing apparatus. For rescue, fire fighting, and other unplanned events, the SCBA shall have an air supply of at least 30 minutes rated duration. For routine work in areas that require SCBA level protection, a combination, full facepiece, pressure-demand, air line respirator with an auxiliary self-contained air supply of at least 10 minutes rated duration may be used. Employees who enter IDLH areas wearing a combination air line/SCBA shall use the air line respirator mode of the apparatus as they work and move about in the IDLH area. The auxiliary cylinder of air is for emergency egress only. Once used, the cylinder shall be refilled. Employees who may be involved in emergency use of SCBA, as in rescue, shall have additional medical tests to measure their reactions under stress and extreme physical exertion.

3.5.6.10 Sample Respirator Program:

Respirator Program

1. PURPOSE:

To establish a respiratory protection program. This document is designed specifically as an implementation plan to insure equipment, testing, training and personnel comply with USACE (ER 385-1-90), OSHA (1910.134), and ANSI (Z88.2-1980) regulations. The process by which each requirement is met for the project is explained below in five sections:

Section I. Assignment of Responsibilities
Section II. Respirator Selection Criteria
Section III. Medical Surveillance of Personnel
Section IV. Respirator Fitting, Testing, and Use
Section V. Training for Respirator Use.

Each section is designed to be used as a checklist to facilitate meeting the program requirements. (It is NOT meant to replace or supersede any existing forms or regulations.) There are also five appendices that provide safety information, data tables, and systems for maintaining documentation.

2. Assignment of Responsibilities. This paragraph provides a checklist of the responsibilities for the Project Manager as well as individual Supervisors.

A. The Project, is responsible to:

______1. Develop a written SOP for care and use of respirators. (Provided in Section IV)

______2. Personally supervise or appoint a qualified individual to coordinate all aspects of the respirator program. (Refer to Section IV)

______3. Review and revise this implementation plan on an ANNUAL basis.

B. The Supervisor as manager of personnel assigned to a crew, is responsible to:

______1. Review job duties and notify personnel and Safety Offices in writing of positions and specific duties which require employees to use respiratory protection.

______2. Assure the use of safety equipment as a provision of the employee's job performance standards.

C. The employee is responsible for:

______1. Wearing a respirator when required, as well a maintaining it properly.

______2. Immediately leaving contaminated areas in the event of respirator malfunction and notifying supervisor.

______3. Taking appropriate medical exams to retain qualification to wear respirators.

3. Respirator selection criteria. This paragraph provides a checklist of criteria necessary for determining proper respirator selection through air monitoring and knowledge of site history.

_____A. Monitor area of respiratory hazard. The use of a continuously operating air monitor with alarms (such as a ________).

_____B. Use tables taken from ER 385-1-90 and CFR 1910.134 (OSHA) to determine proper selection of respirator and filters. Have these tables at the individual shop areas.

4. Medical Surveillance of Personnel. This paragraph provides a checklist to ensure that personnel establish and maintain medical clearance to use respirators.

_____A. All personnel have been medically cleared to use respirators.

_____B. On site documentation of medical clearances is available.

_____C. System is set up for personnel to be re-checked on medical clearance ANNUALLY.

5. Respirator Fitting, Testing, and Proper Use. This paragraph provides a checklist to ensure that proper fitting, testing and maintenance are carried out on schedule.

_____A. All personnel shall be fitted with personal respirators (half-mask, full-mask) assigned specifically to that individual. Positive and negative fit checking is required ANNUALLY by trained tester. Document test results.

_____B. All personnel have been fit tested using personal respirators. Qualitative testing is acceptable (irritant smoke, isoamyl acetate, or saccharine mist). Qualitative testing needs to occur ANNUALLY by trained tester. Quantitative testing needs to occur SEMI-ANNUALLY by trained tester. Document test results.

_____C. Personnel using corrective lenses must be specially fitted for lens inserts. Inserts are to be provided by employer.

_____D. System is set up for respirators to be fit checked and fit tested. (Provided in Appendix C)

_____E. Respirators are cleaned and inspected prior to each use by following proper cleaning procedure. (Refer to Appendix D)

_____F. For each action or project, a qualified individual is placed in charge of the respirator program and specifically supervises respirator use on site. This individual is responsible for:

1. Using monitoring equipment and data, proper respirator system is identified and required for all personnel.

2. All communication systems for use during respirator use are reviewed prior to entering contaminated area.

3. All operational, safety, and rescue procedures are outlined in writing and reviewed with personnel prior to entering contaminated area.

4. Reviewing and maintaining a working knowledge of all the regulations and requirements for the respirator program.

5. Maintaining required documentation of personnel training (respirator training), medical clearance, respirator fitting and testing schedules, and appropriate reference documents.

PROTECTION FACTORS FOR PARTICULATE FILTER RESPIRATORS

Concentrations in multiples of the PEL or TLV	Facepiece Pressure	Permissible Respirators
5x		Single use dust
10x		- Half-mask dust - Half- or quarter mask fume - Half- or quarter mask, high efficiency - Half-mask supplied air
50x		- Full facepiece, high-efficiency - Full facepiece, supplied air - SCBA
1000x	-	Powered, high efficiency, all enclosures
	-	Half-mask, supplied air, Type C positive pressure, demand mode.
2000x	-	Supplied-air with full facepiece, hood, helmet or suit, Type C positive pressure, demand mode
10000x	-	Full facepiece, SCBA
	-	Full facepiece supplied air with auxiliary self-contained air supply
Emergency entry into unknown concentrations	-	Full facepiece SCBA
Escape only 1/	-	Any full facepiece SCBA
	-	Any self-rescuer

1/ In an atmosphere which is immediately dangerous to life or health.

NOTES:

1) Half-mask and quarter-mask respirators should not be used if the particulate matter causes eye irritation at the use concentrations.

2) Full facepiece supplied-air respirators should not be used in any atmosphere which is immediately dangerous to life or health unless it is equipped with an auxiliary air supply which can be operated in the positive pressure mode.

PROTECTION FACTORS FOR GAS OR VAPOR RESPIRATORS

Concentrations in multiples of the PEL or TLV	Facepiece Pressure	Permissible Respirators
10x	-	Half-mask chemical cartridge respirator with "Name" cartridges, or canister half-mask, supplied-air
50x	-	Full facepiece gas mask or chemical cartridge with "Name" cartridges
or		canister.
	-	Full facepiece SCBA Full facepiece supplied-air
1000x	-	Half-mask supplied-air
2000x	-	Supplied-air with full facepiece, hood, helmet or suit
10000x	-	Full facepiece, SCBA
	-	Full facepiece supplied air with auxiliary self-contained air supply
Emergency entry into unknown concentrations	-	Full facepiece SCBA
Escape only 1/	-	Any full facepiece SCBA
	-	Any self-rescuer

1/ In an atmosphere which is immediately dangerous to life or health.

NOTES:

1) The "Name" means approved chemical canisters or cartridges against a specific contaminant or a combination of contaminants such as organic vapor, acid gases, organic vapor plus particulates or acid gases plus organic vapor.

2) Quarter or half-mask respirators should not be used if eye irritation occurs at the use concentration.

3) Full facepiece supplied air respirators should not be used in any atmosphere which is immediately dangerous to life or health unless it is equipped with an auxiliary air tank which can be operated in the positive pressure mode.

4) Air purifying respirators cannot be used for contaminants having inadequate warning properties.

3.5.7 Eye Protection

Helmets, handshields, faceshields, or goggles conforming to ANSI Z87.1 and ANSI Z89.1 shall be used to protect the eyes during spraying or blasting operations. Operators shall use goggles for protection from infrared and ultraviolet radiation and flying particles. Helpers and adjacent operators shall be provided with proper eye protection. The helmet, handshield, or goggles shall be equipped with a suitable filter plate to protect the eyes from excessive ultraviolet, infrared, and intense visible radiation.

3.5.8 Hearing Protection

Protection against the effects of noise exposure shall be provided in accordance with the requirements of EM 385-1-1, Section 5, "Personal Protective and Safety Equipment," Subsection 05.C, "Hearing Protection and Noise Control," and 29CFR Part 1910, Section 95. When personnel are subjected to sound levels exceeding the limits specified in these regulations, feasible engineering or administrative controls shall be employed. Possible alternatives include redesign of equipment, relocation of equipment, changes in metallizing operating conditions, isolation of equipment, and insulation of work areas. If such controls fail to reduce sound levels within the specified limits, personal protective equipment shall be provided and used to reduce sound levels appropriately. Administrative controls such as planning and scheduling may be used to reduce the exposure time. In all cases where the sound levels exceed specified limits, a continuing, effective hearing conservation program shall be administered. The program shall consist of, as a minimum, noise exposure monitoring, employee notification, an audiometric testing program, provision of hearing protectors, employee training programs, and a record keeping program.

3.5.9 Protective Clothing

3.5.9.1 Appropriate protective clothing shall be required for spray or blast operations.

3.5.10 Hazard Communication

The Contractor shall institute a worker hazard communication program for employees in accordance with CFR 29 Part 1910, Section 1200, and state and local worker "right-to-know "rules and regulations. There shall be a written program that describes how the employer will comply with the standard, how chemicals will be labeled or provided with other forms of warning, how MSDSs will be obtained and made available to employees, OSHA and NIOSH representatives, and how information and training will be provided to employees. The program shall include the development of an inventory of toxic chemicals present in the workplace, cross-referenced to the MSDS file. The written program shall also describe how any subcontractor employees and the Contracting Officer will be informed of identified hazards. Specific elements of the program shall include:

3.5.10.1. A file of MSDSs for each hazardous chemical on the chemical inventory, kept in a location readily accessible during each work shift to employees when they are in their work area.

3.5.10.2 Containers of hazardous chemicals in the workplace shall have appropriate labels that identify the hazardous material in the product, have appropriate health and safety warnings, and include the name and address of the manufacturer or responsible party.

3.5.10.3 Training on:

(1) Provisions of the hazard communication standard.

(2) The types of operations in the work areas where hazardous chemicals are present.

(3) The location and availability of the written program and MSDSs.

(4) Detecting the presence or release of toxic chemicals in the workplace.

(5) The visual appearance, odor, or other warning or alarm systems.

(6) The physical and health hazards associated with chemicals in the workplace.

(7) Specific measures to protect from the hazards in the work areas such as engineering controls, safe work practices, emergency procedures, and protective equipment.

3.5.11 Medical Surveillance

Employees required to work with or around solvents, blasting, flame- or arc-spray operations, respiratory equipment, those exposed to noise above 85 dBA continuous or 140 dBA impact, or those who are required to use respiratory protective devices shall be evaluated medically. The Contractor shall provide a written record of the physical examination to all employees that may be required to wear a respirator, those who may be exposed to high noise, or who may be exposed to toxic contaminants. The documentation shall include a statement signed by the examining physician that the employees' exams included the following as a minimum:

(1) Audiometric testing and evaluation.

(2) Medical history with emphasis on the liver, kidney, and pulmonary system.

(3) Testing for an unusual sensitivity to chemicals.

(4) Alcohol and drug use history.

(5) General physical exam with emphasis on liver, kidney, and pulmonary system.

(6) Determination of the employee's physical and psychological ability to wear protective equipment, including respirators, and to perform job-related tasks.

(7) Determination of baseline values of biological indices to include:

(7.1) Liver function tests such as SGOT, SGPT, GCPT, alkaline phosphatase, and bilirubin.
(7.2) Complete urinalysis.
(7.3) EKG.
(7.4) Blood urea nitrogen (BUN).
(7.5) Serum creatinine.
(7.6) Pulmonary function tests, FVC, and FEV.
(7.7) Chest x-ray (if medically indicated).
(7.8) Blood lead (for those individuals who may be exposed to lead).
(7.9) Any other criteria deemed necessary by the Contractor physician and approved by the Contracting Officer.

3.6 CONFINED SPACE PROCEDURES

Point of Entry - Clarification - In November 1994, OHSA published a technical clarification for point of entry or exit to the permit-required confined space standard. The rule defines entry as; the action by which a person passes through an opening into a permit-required confined space. Entry includes ensuing activities in that space and is considered to have occurred as soon as any part of the entrant's body breaks the plane of an opening into a space.

3.6.1. The following standards take precedence over the Permit-Required Confined Space Entry standard for the hazards they address:

29 CFR 1910.120(b)(4)(ii)I The Hazardous Waste Site Specific Safety & Health plan must address confined space entry procedures.
29 CFR 1910.252(a)(4)(i) Removal of arc welding electrodes during suspension of work in confined spaces.
29 CFR 1910.252(b)(4)(i) to (vii) Protection of personnel welding in confined spaces; (ventilation, securing welding equipment, lifelines, electrode removal, gas cylinder shut-off, warnings).

29 CFR 1910.252(c)(4)	Health protection and ventilation during welding operations in confined spaces.
29 CFR 1910.252(c)(9)	Specifies ventilation & respiratory protection requirements for welding in confined spaces using cadmium-bearing filler material.
29 CFR 1910.252(c)(10)	Specifies local exhaust ventilation or respiratory protection for welding & cutting mercury-coated or mercury-bearing materials, including paint, in confined spaces.
29 CFR 1917.152(b)	Requires that work not be performed in confined space until is determined through atmospheric testing, that the space is not hazardous.
29 CFR 1917.152(f)(2)	Requires ventilation & respiratory protection, with standby person, when hot work is done in confined spaces.
29 CFR 1917.152(f)(3)	Specific requirements for welding, cutting, or heating of toxic metals in confined spaces.
29 CFR 1918.93	Addresses entry into storage spaces or tanks where potential hazardous atmospheres exist.

3.6.2. Hazards of Confined Space: Each employee and their supervisor is responsible for implementing policies to properly handle work in permit required confined spaces. In the area of Permit Required Confined Spaces, where one mistake can easily lead to permanent injury or death, it is very important that you **do not deviate in any way from approved and standardized safe operating procedures.**

3.6.3. Testing the Atmosphere: Atmospheric testing is an important part of verifying that permit spaces are safe to enter. Use only approved equipment and maintain and calibrate all testers according to the manufacturers specifications. Safety experts recommend that the first set of tests be performed by remote probe before anyone enters the permit space. Test all areas and levels of the space since heavier hazardous vapors will collect at the bottom while lighter ones will collect at the top.

3.6.3.1. Oxygen Testing

In any permit confined space, test to make sure there is enough oxygen to support life. If the atmospheric concentration is less than 19.5%, OSHA considers the air **oxygen deficient.** If the concentration is greater than 23.5% OSHA considers the air **oxygen enriched.** Air that contains too much oxygen increases the danger of fire.

3.6.3.2. Flammability Testing

After the oxygen test, check the atmospheres' flammability. This is measured in terms of Lower Flammable Limit, or LFL. The LFL is the lowest concentration of a vapor that will explode or burn if it comes in contact with a source of ignition. OSHA considers the atmosphere in a confined space to be hazardous if it contains a vapor concentration more than 10% of the LFL.

3.6.3.3. Toxicity Testing

The third test is for toxicity. If you know of any hazardous substance that have been stored in the space, or could be present in the space, use the appropriate detector to check for those materials. For most materials toxicity is measured in terms of the Permissible Exposure Limit or PEL. This is the concentration of the toxin in the air that most people could safely be exposed to over an eight hour workday and is measured as a Time Weighted Average (TWA). In a confined space any concentration of a toxin greater than its PEL, or other published safety limits, is hazardous.

Gas	**Physical Characteristics**	**LEL % Volume**	**Toxicity (PEL)**
Carbon Monoxide	colorless / odorless	12.5%	35 ppm (0.0035%)
Hydrogen Sulfide	colorless / rotten egg odor	4%	10 ppm (0.001%)
Methane	colorless / odorless	5%	Non-toxic (replaces O2)
Gasoline Vapors	colorless / sweet odor	1%	300 ppm (0.03%)

3.6.4. Ventilation

When the atmosphere of a permit space is hazardous according to any of these tests, the hazard atmosphere must be controlled ***before*** entry is ***allowed.*** Usually this is done with ventilation. If ventilation is used, retest the air with the system on. The procedures for managing work in confined spaces shall include those requirements listed in EM 385-1-1, Section 6, "Hazardous Substances, Agents, and Environments", Subsection 06.I "Confined Space;" and 29CFR 1910.146. Before entry into a confined space, a written procedure shall be prepared, and shall be approved by the Government. The procedure shall include, but not be limited to, the following requirements:

(a) A description of the methods, equipment, and procedures to test for oxygen content and combustible and toxic atmospheres in confined spaces prior to entry and during work.

(b) Emergency procedures for each type of confined space work, including methods of communication, escape, and rescue.

(c) Air monitoring by qualified individuals, and a certificate of calibration for all air monitoring equipment.

(d) Training in confined-space procedures for all affected personnel. Training shall include: confined-space hazards, evaluation of confined-space atmospheres, combustible-gas indicator operation, entry procedures, attendant requirements, isolation and lockout, preparation of confined areas, respiratory protection, communication, safety equipment, no smoking policy, use of entry permits, and appropriate escape and rescue procedures.

(e) Emergency drills prior to confined-space work to ensure the adequacy of the procedures. A rescue test shall be performed to ensure that rescue equipment will fit through the confined-space entrance and to test and practice other confined-space procedures such as communication.

(f) A stand-by person to be present outside the confined space while workers are inside. The attendant shall be trained in the duties of a stand-by person including appropriate rescue procedures. The stand-by person will have no other duty except to attend the entrance of the confined space, be in constant communication with the confined-space workers, and to perform a rescue, if needed, with a self-contained breathing apparatus (minimum air supply of 30 minutes).

(g) Inspection of personal protective equipment prior to entry.

(h) Ventilation of the confined space.

(I) Real-time monitoring of the concentrations of combustible gases or solvent vapors during occupancy.

3.7 SAFETY INDOCTRINATION PLAN

The documentation shall include training records for all personnel employed by the Contractor in the following minimum requirements:
3.7.1 The Contractor's general safety policy and provisions.
3.7.2 Requirements of the employer and contents of EM 385-1-1 section on project safety.
3.7.3 Employer's responsibilities for safety.
3.7.4 Employee's responsibilities for safety.
3.7.5 Medical facilities and required treatment for all accidents.
3.7.6 Procedures for reporting or correcting unsafe conditions.
3.7.7 Procedures for cleaning and surface preparation in a safe manner.
3.7.8 Fire fighting and other emergency training.
3.7.9 Job hazard and activity analysis required for the Accident Prevention Plan.
3.7.10 Alcohol/drug abuse policy.

3.8 DELIVERY, STORAGE, AND HANDLING

3.8.1 Thermal Spray Powder

Thermal spray powder shall be packaged, shipped, and stored in conformance with ASTM D 3951. Commercial packaging shall protect items against physical and environmental damage during shipment, handling, and storage. Thermal spray powder shall be protected against corrosion, deterioration, and damage during shipment. Protection shall be that used for distribution directly to a using customer or subsequent redistribution as required. Individual powder containers and shipping containers shall be clearly and durably labeled to indicate contract numbers, specification number, material type, lot number, net weight, date of manufacture (month and year), and manufacturer's or distributor's name. Thermal spray powder shall be stored under cover and protected from the elements.

3.8.2 Solvents

Solvents and other flammable materials shall be stored in approved, labeled containers. Local exhaust ventilation shall be provided, where practical, to remove such gases or vapors at the source. Exhaust ducts shall discharge clear of working areas and away from sources of ignition. Electric motors for exhaust fans shall not be placed in areas where flammable materials are being used. Fans shall have nonferrous blades. Portable air ducts shall be constructed of nonferrous materials. Motors and associated control equipment shall be properly maintained and grounded. Dilution ventilation may be used to reduce the concentration of vapors to below the lower

explosive limit (LEL). Dilution ventilation rates to control explosive hazards shall not be applied in those situations where workers are exposed to the vapor. In those cases, the more stringent threshold limit value (TLV) or permissible exposure limit (PEL) shall be used for health hazard control. Sources of ignition shall not be permitted in areas where flammable liquids are stored, handled, and processed. Suitable NO SMOKING OR OPEN FLAME signs shall be posted in all such areas. Suitable fire extinguishing equipment shall be immediately available in the work area and shall be maintained in a state of readiness for instant use by appropriately trained workers.

3.8.3 Pressure Systems

3.8.3.1 Compressed gas cylinders shall be handled in accordance with ANSI Z49.1 and with CGA P-1. Only special oxidation-resistant lubricants may be used with oxygen equipment; grease or oil shall not be used.

3.8.3.2 Manifolding and pressure reducing regulators, flow meters, hoses, and hose connections shall be installed in accordance with ANSI Z49.1. A protective shield shall be placed between a glass tube flow meter and the spray gun. Pressure connecting nuts shall be drawn up tight, but not overtightened. If a fitting cannot be sealed without excessive force, it shall be replaced. Compressed air for thermal spraying or blasting operations shall be used only at pressures recommended by the equipment manufacturers. The air line should be free of oil and moisture. Compressed air, oxygen, or fuel gas shall not be used to clean clothing.

3.8.4 Thermal Spray Equipment

3.8.4.1 Thermal spray equipment shall be maintained and operated according to the manufacturer's instructions. Thermal spray operators shall be fully trained in and familiar with specific equipment before starting an operation. Valves shall be properly sealed and lubricated. Friction lighters, pilot light, or arc ignition methods of lighting thermal spray guns shall be used. If a gun backfires, it shall be extinguished as soon as possible. Re-ignition of a gun that has backfired or blown out shall not be attempted until the cause of the trouble has been determined. Thermal spray guns or hoses shall not be hung on regulators or cylinder valves. Gas pressure shall be released from the hoses after equipment is shut down or left unattended.

3.8.4.2 Oil shall not be allowed to enter the gas mixing chambers when cleaning flame-spray guns. Only special oxidation-resistant lubricants shall be used on valves or other parts of flame-spray guns that are in contact with oxygen or fuel gases.

3.8.5 Ventilation

Local exhaust or general ventilation systems shall be provided to control toxic fumes, gases, or dusts in any operations not performed in the open. When toxic particulates are removed from a

work area, a dust collector shall be used to trap the dust and prevent contamination of the surrounding areas and the general environment.

3.8.6 Toxic Materials

Metallizing shall be done only with appropriate respiratory protection and adequate ventilation. Spraying such metals as cobalt, nickel and tungsten in an enclosed space shall be performed with general mechanical ventilation, air line respirators, or local exhaust ventilation sufficient to reduce the fumes to safe limits specified by ACGIH-02. Employee exposures shall be controlled to the safe levels recommended by ACGIH-02 or prescribed by CFR 29 Part 1910, whichever is more stringent.

3.9 AIR SAMPLING

Air sampling shall be performed before entry to any confined space, during confined-space entry that involves contaminant-generating operations such as flame-spray operations, and in areas where ventilation is inadequate to ensure that air contaminants will not accumulate.

4 PRODUCTS

4.1 SAMPLING AND TESTING

4.1.1 General

Batches or lots of thermal spray powder shall be stored at the project site or segregated at the source of supply sufficiently in advance of need to allow 14 days for sampling and testing. The Contractor shall notify the Contracting Officer when the thermal spray powder is available for sampling. All sampling shall be performed in accordance with MIL-STD 105. For sampling purposes, the unit of product shall be a container of powder. Sampling of each lot will be witnessed by a representative of the Contracting Officer unless otherwise specified or directed. Samples of thermal spray powder submitted for approval shall be clearly labeled to indicate type of coating material, lot number, date, and name of manufacturer, total weight represented by lots, and contract number.

4.1.2 Sprayed Coating

If any of the thermal sprayed coating 1/2 inch square (160 sq. mm) or larger can be lifted from the substrate with a knife or chisel, without actually cutting the metal away, the adhesion will be deemed deficient. At the Contracting Officer's discretion, thermal sprayed coating systems may also be tested for adhesive strength in accordance with ASTM C 633. If so tested, the adhesion

shall be 5000 psi (22,240 Pascal). Thermal-sprayed surfaces which have been rejected for poor adhesion shall be blast cleaned and recoated. The test plate will also be used as a working standard to determine the acceptability of work in progress and the completed job. In the event that the Contractor's metallic coating is inferior to the accepted sample, the Contractor shall be required to correct the coating by an approved repair method.

5. MAJOR REQUIREMENTS:

Using High Velocity Oxygen Fuel type spray process, the Contractor shall apply [Stellite® 6] in accordance with this specification. In order to accomplish this work, it shall be necessary for the Contractor to perform the following tasks:

5.1 COORDINATION MEETING

The Contractor shall attend a coordination meeting with the Contracting Officer, worksite personnel, and USACERL personnel or their designates before start of work. Meeting date and time will be mutually agreed upon by the participants. The purpose is to review the work procedures and areas to be coated, any other technical issues, and safety and operational concerns.

5.2 SITE PREPARATION

5.2.1 Elevator and crane service to the staging area [will/will not] be available to the contractor. [At the Contractor's option, the Contractor may supply an electric crane, up to 2 ton capacity, to assist in moving equipment to the staging area. The crane will be tested in accordance with EM 385-1-1.]

5.2.2 The area at the turbine [will/shall] be prepared by [resident/contractor] personnel by supplying a platform suspended below the turbine blades. This platform shall have a load rating that will provide safe support to personnel and equipment.

[5.2.3 The Contractor shall supply lighting for the general area and task lighting for the surface preparation, coating application and inspections.]

5.3 SURFACE PREPARATION

5.3.1 [The turbine will be dewatered by dam personnel. The surface of the blades and throat ring will have residual water and potentially residual river debris such as silt particles which are unacceptable for thermal spray coating application.] Any moisture and debris shall be removed prior to thermal spray coating application. The Contractor shall use the submitted and approved

surface preparation procedure. It should describe how the resulting surface finish will have an angular grit blasted surface with a minimum of 300 microinches Ra over a 0.100 inch travel with a waviness cut off of 0.030 inches.

5.3.2 Surfaces to be metallized shall be clean before application of metallic coatings. The removal of oil and grease shall be accomplished with mineral spirits or other low toxicity solvents having a flash-point above 100 degrees F before abrasive cleaning is started. Solvent cleaning shall be done with clean cloths and clean fluids to avoid leaving a thin film of greasy residue on the surfaces being cleaned. Cleaning, and metallizing shall be so programmed that dust, dry spray, or other contaminants from the cleaning and painting operations do not contaminate surfaces ready for metallization or painting. Surfaces not intended to be metallized shall be suitably protected from the effects of cleaning and metallizing operations. Machinery shall be protected against entry of blast abrasive and dust into working parts.

5.3.3 The Contractor shall supply all necessary and appropriate grit blast equipment including grit hoppers, grit blast guns including all consumable parts, hoses, electrical lines and cables and necessary safety equipment.

5.3.4 The Contractor shall grit blast the areas to be coated. The grit blast operation will use non-recycled grit to prevent contamination. Grit blast media will be removed from the platform on a continual basis. The weight of the grit, equipment and personnel on the platform at any time shall not exceed the load rating of the platform.

5.3.5 The Government may inspect the grit blasted surface prior to the application of coating. The contractor shall notify the Contracting Officer for Government approval prior to coating application. The surface will be compared to previously prepared grit blasted standard for surface texture. The grit blasted surface will be free of moisture, oil and debris contamination including dust or grit particles settled on the surface. The Contractor shall use the procedure submitted and approved under section 3.3.3.1.

5.3.6 Ferrous surfaces to be metallized shall be dry blast cleaned to a white metal grade in accordance with SSPC SP 6. All surfaces to be metallized shall be blast cleaned to the specified surface profile as measured by ASTM D 4417, Method C. Weld spatter not dislodged by blasting shall be removed with impact or grinding. Surfaces shall be dry at the time of blasting. Within 4 hours of blasting, and prior to the deposition of any detectable moisture, contaminants, or appearance of corrosion, all ferrous surfaces that have been blast cleaned to the white metal grade shall be cleaned of dust and abrasive particles by brushing, vacuum cleaning, and/or blowdown with clean, dry compressed air, and given the first spray of metallic coating.

5.4 THERMAL SPRAY APPLICATION

5.4.1 General

The thermal spray coating shall have a uniform appearance. The coating shall not contain any of the following: blisters, cracks, chips or loosely adhering particles, oils or other internal contaminants, pits exposing the substrate, or nodules. All metallizing coats shall be applied in such a manner as to produce an even, continuous film of uniform thickness tapering down within 4 inches of the edge of the coating. Thermal spray equipment shall be operated using qualified personnel in accordance with the manufacturer's recommendations. Metallizing and welding in the vicinity of previously painted metallized surfaces shall be conducted in a manner that prevents molten metal from striking the paint and otherwise minimizes paint damage. Paint damaged by welding or metallizing operations shall be restored to original condition. Metallizing shall not extend closer than 3/4 inch (20 mm) to surfaces that are to be welded.

5.4.1.1 The coating [Stellite® 6] shall be applied to an average thickness of 20.0 mils for the completed system. The thickness at any one point shall not be less than 15.0 mils with the exception of edge feathering as stated in Section 5.5.2.1. Alternate spray passes shall be applied at right angles until the specified coating thickness is achieved.

5.4.1.2 Atmospheric and Surface Conditions

Metallic coating shall be applied only to surfaces that are a minimum of 5 ºF above the dew point and that are completely free of moisture as determined by sight and touch. Metallic coating shall not be applied to surfaces upon which there is detectable frost or ice.

5.4.1.3 Time Between Surface Preparation and Metallizing

Surfaces that have been prepared for metallizing shall receive the first coat of metallic coating as soon as practicable after surface preparation has been completed. The first coat shall be applied prior to the appearance of flash rust or within 4 hours of abrasive blasting, whichever is sooner.

5.4.2 Application of Thermally Sprayed Coating

5.4.2.1 The specific area to be coated will be defined by Contracting Officer in the coordination meeting. The location of the edges of the coated area adjacent to the uncoated areas are defined to within 3 inches. Masking shall only be used in an area of at least 1 foot extending from the blade roots. On the other edges of the coating, the transition from coating to no coating will be feathered over an area of 1 to 4 inches. This will allow the coating to transition from the projected .020 inch thickness to zero coating thickness.

5.4.2.2 The Contractor shall apply the coating system in accordance with the application parameters submitted and approved by the Contracting Officer. These application parameters shall be within the normal operating range for the HVOF application equipment.

5.4.2.3 Coverage and Metallized Coating Thickness

Coating thickness shall be measured in accordance with SSPC PA 2, and shall be measured with one of the gauges listed below. Gauges shall be calibrated on metal substantially the same in composition and surface preparation to that being coated and of similar thickness, or have a minimum thickness of 0.25 inch (0.64 cm). Calibration thickness standards (shims) shall be of a metallic composition similar to that of the material being sprayed. Where only one thickness is specified (i.e., either a minimum or an average), the calibration shim's thickness shall closely approximate the specified thickness. Where two thicknesses are specified, the shim's thickness shall closely approximate an average of the two. Calibration instructions, thickness standards, and in the case of the Mikrotest gauge, a calibration tool shall be obtained from the manufacturer or supplier of the gauge. Authorized thickness gauges are:

(1) General Electric, Type B, General Electric Company.

(2) Mikrotest, Electrophysik-Koln.

(3) Elcometer, Elcometer Instruments, Ltd.

(4) Inspecter Gauge, Elcometer Instruments, Ltd.

(5) Minitector, Elcometer Instruments, Ltd.

(6) Positector 2000, DeFelsko Corporation.

5.4.3 Thermal Spray Quality Control

5.4.3.1. In addition to the Quality Control Plan, Documentation, Section 14.1.9, the Contractor shall submit copies of the following certifications forms:

(1) Powder physical characteristics, including chemistry, powder particle size, powder type, manufacturer or supplier, manufacturer's reference or stock numbers and lot numbers.

(2) For each of the lots of grit including chemistry or type, grit particle size, manufacturer or supplier, manufacturer's reference or stock numbers and lot numbers.

(3) For each of the lots of gas used in the performance of the contract including chemistry, manufacturer or supplier, manufacturer's reference or stock numbers and lot numbers.

5.4.3.2 Samples of Powder and Grit

The Contractor shall supply a sample of not less than 250 grams of each of the lots of the powders and grit actually used on the job. These samples will be used only for laboratory analysis purposes by the government and not for acceptance criteria.

5.4.3.3 Samples for Acceptance Criteria.

The Contractor shall use the submitted and approved surface preparation and the thermal spray procedures to prepare samples for quality acceptance. The Contractor shall use the submitted and approved inspection plan to evaluate these samples. Final acceptance shall be made by the Contracting Officer.

6 START DATE

The period of performance will be between [__________ and ___________]. The Contractor may begin to mobilize on-site before the start date. The Contractor shall completely vacate the Government premises by [__________].

7 WORK ON A GOVERNMENT INSTALLATION

7.1 INSURANCE

7.1.1 The Contractor shall, at its own expense, provide and maintain during the entire performance of this contract at least the following kinds and minimum amounts of insurance.

7.1.1.1 Workmen's Compensation and Employer's Liability Insurance in the minimum amount of $300,000.

7.1.1.2 Comprehensive bodily injury and property damage liability; minimum limits of $1,000,000 for injury to or death of any person and $2,000,000 for each accident or occurrence for bodily injury liability; and $300,000 for each accident or occurrence for property damage liability.

7.1.1.3 Automobile bodily injury and property damage liability; minimum limits of $1,000,000 for injury to or death of any one person and $2,000,000 for each accident or occurrence for bodily injury; and $100,000 for each accident or occurrence for property damage liability.

7.2 INSURANCE CERTIFICATION

Before commencing work under this contract, the Contractor shall certify to the Contracting Officer in writing that the required insurance has been obtained. The policies evidencing required insurance shall contain an endorsement to the effect that any cancellation or any material change adversely affecting the Government's interest shall not be effective (1) for such period as the laws of the State which this contract is to be performed, prescribed, or (2) until 30 days after the insurer or the Contractor gives written notice to the Contracting Officer, whichever period is longer.

7.3 INSERTION OF CLAUSES

The Contractor shall insert the substance of this clause, including this paragraph, in subcontracts under this contract that require work on a Government installation and shall require subcontractors to provide and maintain the insurance required in the Schedule or elsewhere in the contract. The Contractor shall maintain a copy of all subcontractors' proofs of required insurance, and shall make copies available to the Contracting Office upon request. (FAR 52.228-5).

8. PRE-PERFORMANCE CONFERENCE. Within 3 working days after the date of receipt of signed contract, call the Contracting Officer, and make arrangements for a pre-performance conference to be held [_______________]. The purpose of the conference is to verify submittal requirements, discuss construction and testing procedures, shop drawings, administration of the system, interrelationship of Contractor Quality Control and Government Quality Assurance, and to develop mutual understanding relative to details of the CQC system, including the forms to be used for recording the CQC operations.

9 POINT OF CONTACT: The technical point of contact is the Government Quality Assurance Representative (GQAR). No government personnel other than the Contracting Officer will have the authority to modify any terms of the contract, or to do other than clarify technical points or supply relevant information. Specifically, no requirement in this statement of work may be altered as a sole result of verbal clarifications.

10 PERIOD OF SERVICE: The contractor may begin delivering and storing equipment at [__________] Powerhouse after [____________]. The Government will provide access to the worksite after [___________]. All work to be performed under this contract shall be completed by [__________].

11 CONTRACTOR'S OPERATIONS

11.1 GENERAL. This section covers the general requirements applicable to specific Contractor's operations or equipment for work performed at the [________].

11.2 WORK AREA AND ACCESS

11.2.1 Access Roads. Access to [(worksite)] by the Contractor's personnel shall be from [______________]. Checking on possible transportation restrictions is the Contractor's responsibility. The existing access roadways shall not be closed as a result of activities associated with this contract. Traffic delays will only be permitted in accordance with the provisions of this section. In the event that existing roadways used for access purposes are damaged, the damages shall be repaired and the surfaces shall be restored to their original grade and condition. All access roads shall be available for use by Government personnel. In addition to SECTION I, Contract Clause, ACCIDENT PREVENTION (Alternate 1), when necessary for equipment to operate on or to cross access roads, arterial roads, or highways; (11.2.1. cont'd) flaggers, signs, lights and/or other necessary safeguards shall be furnished to safely control and direct the flow of traffic. All work shall be conducted so as to minimize obstruction of traffic. Should the Contractor require the additional working space or lands on the project for material yards, offices, or other purposes, they shall be obtained through mutual agreement between the Contractor and the Government. The buildings and grounds shall be kept in orderly and sanitary condition.

11.2.2 Access By Government Personnel. Clear access shall be maintained for Government personnel and equipment through the work areas. Passage shall not be blocked by Contractor's equipment or operations for more than 10 minutes without prior approval.

11.2.3 Employee Access. Worksite areas off-limits to Contractor's personnel will be designated at the pre-performance conference.

11.2.4 Worksite Access. The Contractor may work any hours preferred, but shall make arrangements with the GQAR for hours other than usual worksite hours. The GQAR shall be notified at least 48 hours in advance of any change in the contractor's schedule.

11.3 ROAD USE AND OTHER RESTRICTIONS

11.3.1 Facility Security. The facility is open to the public [from _______ to _______, _______ through __________], except Federal holidays. A procedure for control of Contractor's employees entering or leaving the project during the hours of closure shall be submitted for approval in accordance with SECTION [____, paragraph _____] except submittal shall be a minimum of 20 days prior to the beginning of work. Arrangement and scheduling of working hours and crews shall be in accordance with the approved procedure.

11.3.2 Identification of Vehicles. In order to keep proper control of vehicles in the work area, all Contractor's vehicles shall display suitable permanent identification. Identification shall be as approved.

11.3.3 Use of Private Vehicles. Parking of private vehicles of the Contractor and Contractor's employees shall be restricted to areas designated at the pre-performance conference.

11.3.4 Government Roadways. Access to the Contractor's work areas will be available from [___________________]. Unless otherwise approved, the roadways on the site are subject to a load limitation equivalent to [the State Highway HS-20 loading/ _________________]. For cranes in excess of 50 tons capacity, a loading diagram shall be submitted for review and approval showing the travel wheel loads. If the crane travel wheel loads exceed the roadway allowable loads, the crane will not be permitted to travel on the roadway.

11.4 SANITARY FACILITIES. Use of worksite restrooms by the Contractor's personnel [will/will not] be permitted. Portable sanitary facilities [are not/are] permitted.

11.5 UTILITIES: will be Government or contractor furnished as noted below. All contractor-furnished temporary utilities shall be provided and maintained in accordance with appropriate sections of
EM 385-1-1.

[Water]
[Electricity]
[Compressed air]
[__________]

11.7 CONTRACTOR'S CRANE

11.7.1 Crane Testing. All of the Contractor's cranes shall be tested in accordance with EM 385-1-1 prior to use on Government property and shall be witnessed by the GQAR. The contractor shall notify the contracting officer at least 48 hours (excluding weekends and federal holidays) in advance of the test .

11.8 COOPERATION. The Government will be performing maintenance work and will make every effort to have the area clear. The Contractor shall cooperate with other Contractors and the Government in using the area.

11.9 GOVERNMENT WORK SCHEDULES. Resident personnel generally work [___________ to ________, __________ through ___________], except Federal holidays.

11.10 PRECAUTIONS. The work under this contract is at [(worksite)] and subject to the safety clearances and operating procedures currently practiced by this facility. All the activities shall be coordinated with the GQAR and the Project Engineer so that the work will not adversely affect the daily operation of the facility. Safety clearances must be in place before opening, entering or working on any existing equipment or water passage. All working areas shall be kept clean and orderly at all times. Tools and construction equipment shall be put away at the end of each workday.

11.11 CONTRACTOR'S WORK SCHEDULE. A minimum of 5 working days prior to commencement of work, a proposed schedule of work hours and days of the week for work at the project site shall be furnished. Any changes of schedule of regular work hours, overtime work hours, and shifts of work crews and personnel shall be furnished a minimum of 48 hours prior to any schedule change to allow suitable scheduling of Government personnel and inspection. Exception to this requirement may be allowed in case of schedule change due to emergency conditions.

11.12 DAILY CLEANUP AND DISPOSAL. All debris resulting from work, such as waste metalwork, concrete chips, scrap lumber, oil and grease spills, and other debris shall be collected, removed, and disposed of off site at least once per shift. The Government's trash cans, dumpsters, etc. shall not be used. Liquid waste shall not be disposed of in powerhouse drains.

12 ENVIRONMENTAL PROTECTION

12.1 GENERAL

This section covers general and special regulations for preventing environmental water, air and ground pollution.

12.1.1 Applicable Regulations

All environmental water, air and ground pollution shall be prevented, abated and controlled by complying with all applicable Federal, State, and local laws and regulations concerning

environmental water, air and ground pollution control and abatement, as well as the specific requirements in this contract.

12.1.2 Submittals

Submittals required by this section of the Technical Specifications shall be for Government approval (GA) or for information only (FIO), and shall be submitted as stated below.

(1) Environmental Protection Plan (GA). An Environ-mental Protection Plan for environmental water protection, water, air and ground pollution at the [________] Powerhouse shall be submitted in letter form.

12.1.3 Noncompliance

An order stopping all or part of the work may be issued for failure to comply with the provisions of this section until corrective action has been taken. No time lost due to such stop orders or stop orders issued by any appropriate Federal, State or local environmental protection agency shall be the subject of a claim for extension of time or for costs or damages unless it is later determined that the Contractor was in compliance.

12.1.4 Subcontractors

Compliance with this section by subcontractors will be the responsibility of the Contractor.

12.2. PRODUCTS

12.2.1 Material Safety Data Sheets (MSDS)

MSDS shall be provided for all applicable materials which are brought on site.

12.3. IMPLEMENTATION

12.3.1 Protection of Water Resources

No water courses shall be polluted or have existing pollution contributed to with any petroleum products, oils, lubrications, lead based paint, or other toxic materials harmful to life. Chemical emulsifiers, dispersants, coagulants, or other cleanup compounds shall not be used without prior written approval. Compliance with the State of Washington water quality standards and conditions of any permits and clearances obtained for the work is the Contractor's responsibility.

12.3.2 Protection of Land Resources

The land resources within the project boundaries and outside the limits of permanent work performed under this contract shall be preserved in their present condition or be restored to a condition after completion of construction that will appear to be natural and not detract from the appearance of the project. The Contractor shall confine his construction activities to areas defined by the plans of specifications or as approved.

12.3.3 Disposal of Any Hazardous Waste

The following shall apply to disposal of any hazardous waste:

(1) The Contractor, where possible, will use or propose for use materials which may be considered environmentally friendly in that waste from such materials is not regulated as a hazardous waste or is not considered harmful to the environment.

(2) Documentation for analysis, sampling, transpor-tation, and disposal of all hazardous waste streams generated during this contract shall be in accordance with 40 CFR parts 260 through 272.

(3) A copy of all hazardous waste determinations, sample results, and shipping manifests shall be furnished to the GQAR to verify compliance with Federal, State, and local regulations.

(4) All hazardous wastes shall be removed from the Project for proper disposal within 90 days of waste generation.

(5) Certificates of Destruction or Disposal Certifi-cates shall be submitted for all hazardous wastes within 14 days of actual disposal.

(6) The Contractor's EPA identification number shall be used to dispose of all hazardous wastes (HW) generated by the Contractor and its contractors under this contract. This is construed to mean all hazardous wastes the Contractor or subcontracts generate from materials brought on the site for the purpose of performing work under the terms of the contract.

(7) The Government's EPA identified number shall be used by the Contractor to dispose of all hazardous waste (HW) generated from Government-owned facilities on the project. This is construed to mean hazardous wastes generated form the repair, demolition, or removal of any existing materials and buildings from Government facilities and is not intended to include any wastes generated by the Contractor in the performance of its work.

13. INSPECTION AND ACCEPTANCE

13.1. SUPPLY QUALITY MANAGEMENT, CONTRACTOR QUALITY CONTROL

13.1.1 General Information. A Contractor's Quality Control (CQC) system shall be established and maintained in compliance with paragraph E-5. The CQC system shall include but not be limited to plans, procedures, and organization necessary to produce an end product which complies with the contract requirements. The CQC system shall cover both on-site and off-site operations, and shall be keyed to the proposed work sequence.

13.1.2 Quality Control Plan.

13.1.2.1 General. The CQC plan which is proposed to implement the requirements of paragraph E-5, shall be submitted for review not later than 15 days after receipt of signed contract. The plan shall identify personnel, procedures, instructions, tests, records, and forms to be used. The Government will consider an interim plan for the first 10 days of operation. Work will be permitted to begin only after acceptance of the CQC Plan or acceptance of an interim plan applicable to the particular feature of work to be started. Work outside of the features of work included in an accepted interim plan will not be permitted to begin until acceptance of a CQC Plan or another interim plan containing the additional features of work to be started.

13.1.2.2 The Contractor's Quality Control (CQC) Plan. The CQC plan shall include as a minimum the following to cover all work, both on site and off-site, including work by subcontractors, fabricators, suppliers, and purchasing agents:

(1) A description of the CQC organization, including a chart showing the lines of authority and acknowledgment that the CQC staff known as Contractor Quality Control Representatives (CQCRs) shall implement the three- phase control system for all aspects of the contract work. The staff shall include a CQC system manager who shall report to the project manager or someone higher in the Contractor's organization. Project manager shall mean the individual with responsibility for the overall management of the project, including quality and production.

(2) The name, qualifications (in resume format), duties, responsibilities, and authorities of each person assigned a CQC function.

(3) A copy of the letter to the CQC system manager signed by an authorized official of the firm which describes the responsibilities and delegates sufficient authorities to adequately perform the functions of the CQC system manager including authority to stop work which is not in compliance with the contract. The CQC system manager shall issue letters of direction to all other quality control representatives outlining duties, authorities and responsibilities. Copies of these letters shall be furnished to the Government.

(4) Procedures for scheduling, reviewing, certifying, and managing submittals, including those of subcontractors, off-site fabricators, suppliers and purchasing agents.

(5) Control, verification and acceptance testing pro-cedures for each specific test to include the test name, specification paragraph requiring test, feature of work to be tested, test frequency, and person responsible for each test.

(6) Procedures for tracking preparatory, initial, and follow-up control phases and control, verification, and acceptance tests including documentation.

(7) Procedures for tracking deficiencies from identification through acceptable corrective action. These procedures will establish verification that identified deficiencies have been corrected.

(8) Reporting procedures, including proposed reporting formats.

(9) A list of the definable features of work. A definable feature of work is a task which is separate and distinct from other tasks and has separate control requirements. It could be identified by different trades or disciplines, or it could be work by the same trade in a different environment. Although each section of the specifications may generally be considered as a definable feature under a particular section. This list will be agreed upon during the coordination meeting.

13.1.2.3 Acceptance of Plan. Acceptance of the CQC plan is required prior to the start of work. Acceptance is conditional and will be predicated on satisfactory performance during the contract. The Government reserves the right to require the Contractor to make changes in the CQC plan and operations including removal of personnel, as necessary, to obtain the conformance with contract requirements.

13.1.2.4 Notification of Changes. After acceptance of the CQC plan, any proposed changes shall be submitted for acceptance a minimum of 7 calendar days prior implementing to any proposed change.

13.1.3 Coordination Meeting. After the pre-performance conference and before the start of the work, the Government and the Contractor shall meet to discus and develop a mutual understanding of the CQC system in detail, and the interrelationship of Contractor's management and control with the Government's quality assurance. Minutes of the meeting which will be prepared by the Government and shall be signed by both the Contractor and the Government, shall become a part of the contract file. There may also be occasions when subsequent conferences will be called by either party to reconfirm mutual understandings and/or address deficiencies in the CQC system or procedures which may require corrective action by the Contractor.

13.1.4 Quality Control Organization. An individual shall be identified within the Contractor's organization at the site of the work who shall be responsible for the overall management of CQC known as the CQC manager and shall have the authority to act in all CQC matters for the contractor. This CQC system manager will be employed by the Contractor and shall be on the site at all times during the contract. An alternate for the CQC System Manager will be identified in the plan to serve in the event of the system manager's absence. Period of absence may not exceed 3 weeks at any one time, and not more than 4 workdays during a calendar year. The requirements for the alternate will be the same as for the designated CQC manager.

13.1.5 Submittals. Submittals shall be as specified elsewhere in this solicitation. The CQC organization shall be responsible for certifying that all submittals are in compliance with the contract requirements.

13.1.6 Control. CQC is the means by which the Contractor ensures that the work, to include that of subcontractors and suppliers, complies with the requirements of the contract. The controls shall be adequate to cover all operations, including both on-site and off-site fabrication, and will be keyed to the proposed work sequence. The controls shall include at least three phases of control to be conducted by the CQC system manager for all definable features of work, as follows:

(1) Preparatory Phase. This phase shall be performed prior to beginning work on each definable feature of work and shall include:

(a) A review of each paragraph of applicable specifications.

(b) A review of the contract plans.

(c) A check to assure that all materials and/or equipment have been tested, submitted, and approved.

(d) A check to assure that required control inspection and testing are provided.

(e) Examination of the work area to assure that all required previous work has been completed and is in compliance with the contract.

(f) A physical examination of required materials, equipment, and sample work to assure that they are on hand, conform to approved shop drawing or submitted data, and are stored as specified.

(g) A review of the appropriate activity hazard analysis to assure that safety requirements are met.

(h) Discussion of procedures for the work feature including but not limited to tolerances and workmanship standards for that work feature.

(i) A check to ensure that the portion of the plan for the work to be performed has been submitted and accepted.

(j) The Government shall be notified at least 48 hours in advance of beginning any of the required action of the preparatory phase. This phase shall include a meeting conducted by the CQC personal (as applicable), and the individual responsible for the definable feature. The results of the preparatory phase actions shall be documented by separate minutes prepared by the CQC system manager and attached to the daily CQC report. The applicable workers shall be informed as to the acceptable level of workmanship required in order to meet contract specifications prior to the start of actual work.

(2) Initial Phase. This phase shall be accomplished at the beginning of a definable feature of work. The following shall be accomplished:

(a) A check of preparatory phase work to ensure that it is in compliance with contract requirements. Review minutes of the preparatory meeting.

(b) Verification of full contract compliance. Verify required control inspection and testing.

(c.) Establish level of workmanship and verify that it meets minimum acceptable workmanship standards. Compare with sample panels is appropriate.

(d) Resolve all differences.

(e) Check safety to include compliance with and upgrading of the safety plan and activity hazard analysis. Review the activity analysis with each worker.

(f) The Government shall be notified at least 48 hours in advance of beginning the initial phase. Separate minutes of this phase shall be prepared by the CQC system manager and attached to the daily CQC report. Exact location of initial phase shall be indicated for future reference and comparison with follow-up phases.

(g) The initial phase should be repeated fro each new crew to work on-site, or any time specified quality standards are not being met.

(3) Follow-up Phase. Daily checks shall be performed on the ongoing work to assure continuing compliance with contract requirements, including control testing, until completion of the particular feature of work. The checks shall be made a matter of record in the CQC documentation. Final follow-up checks shall be conducted and all deficiencies corrected prior to the start of additional features of work which may be affected by the deficient work. The Contractor shall not build upon or conceal non-conforming work.

(4) Additional Preparatory and Initial Phases. Additional preparatory and initial phases may be conducted on the same definable features of work as determined by the Government if the quality of on-going work is unacceptable; or if there are changes in the applicable CQC staff or in the on-site production supervision or work crew; or if work on a definable feature is resumed after substantial period of inactivity, or if other problems develop.

13.1.7 Tests

13-1.7.1 Testing Procedure. Tests that are specified or required shall be performed to verify that control measures are adequate to provide a product which conforms to contract requirements. Testing includes operation and/or acceptance tests when specified. The Contractor shall procure the services of a Corps of Engineers approved testing laboratory or establish an approved testing laboratory at the job site. A list of tests to be performed shall be furnished as a part of the CQC plan. The list shall give the test name, frequency, specification paragraph containing the test requirements, the personnel and laboratory responsible for each type of test, and an estimate of the number of tests required. The following activities shall be performed and recorded and the following data provided:

(1) Verify that testing procedures comply with contract requirements.

(2) Verify that facilities and testing equipment are available and comply with testing standards.

(3) Check test instrument calibration data against certified standards.

(4) Verify that recording forms and test identification control number system, including all of the test documentation requirements, have been prepared.

(5) Results of all tests taken, both passing and failing tests, will be recorded on the CQC report for the date taken. Specification paragraph reference, location where tests were taken, and the sequential control number identification the test will be given. Actual test reports may be submitted later, if approved, with a reference to the test number and date taken. An information copy of tests performed by an off-site or commercial test facility will be provided directly to the Government. Failure to submit timely test reports, as stated, may result in nonpayment for related work performed and disapproval of the test facility for this contract.

13-1.7.2 Testing Laboratories.

(1) Capability Check. The Government reserves the right to check the laboratory equipment in the Contractor's proposed laboratory for compliance with the standards set forth in the contract specifications and to check the laboratory technician's testing procedures and techniques. Laboratories utilized for testing soils, concrete, asphalt, and steel shall meet criteria detailed in ASTM D 3740 and ASTM E 329.

(2) Capability Recheck. If the selected laboratory fails the capability check, the Contractor will be assessed a charge equal to the cost to the Government for the initial test, to reimburse the Government for each succeeding recheck of the laboratory or the checking of a subsequently selected laboratory. Such costs will be deducted from the contract amount due the Contractor.

13.1.8 Completion Inspection. At the completion of all work or any increment thereof established by a completion time stated in SECTION F or stated elsewhere in the specifications, the CQC manager shall conduct an inspection of the work and develop a "punch list" of items which are incomplete and/or do not conform to the approved plans and specifications. Such a list shall be included in the CQC documentation, as required by paragraph E-1.9, and shall include the estimated date by which the deficiencies will be corrected. The CQC system manager or staff shall make a second inspection jointly with the GQAR to ascertain that all deficiencies have been corrected and submit a record of the inspection to the GQAR. These inspections and any deficiency corrections required by this paragraph shall be accomplished within the time stated for completion of the entire work or any particular increment thereof, if the project is divided into increments by separate completion dates.

13.1.9 Documentation.

13.1.9.1 Current records of CQC operations, activities, and tests performed shall be maintained including the work of subcontractors and suppliers. These records shall be on an approved form and shall include factual evidence that required quality control activities and/or tests have been performed, including but not limited to the following:

(1) Contractor/subcontractor and their area of respon-sibility.

(2) Operating plant/equipment with hours worked, idle, or down for repair.

(3) Work performed today, giving location, description, and by whom. When Network Analysis (NAS) is used, identify each phase of work performed each day by NAS activity number.

(4) Test and/or control activities performed with results and references to specifications/plan requirements. The control phase should be identified (Preparatory, Initial, Follow-up). List deficiencies noted along with corrective action.

(5) Material received with statement as to its accept-ability and storage.

(6) Identify submittals reviewed, with contract refer-ence, by whom, and action taken.

(7) Off-site surveillance activities, including actions taken.

(8) Job safety evaluations stating what was checked, results, and instructions or corrective actions.

(9) List instructions given/received and conflicts in plans and/or specifications.
(10) Contractor's verification statement.

(11) These records shall indicate a description of trades working on the project; the number of personnel working; weather conditions encounters; and any delays encountered. These records shall cover both conforming and deficient features and shall include a statement that equipment and materials incorporated in the work and workmanship comply with the contract. The original and one copy of these records in report form shall be furnished to the Government daily within 24 hours after the date(s) covered by the report, except that reports need not be submitted for days on which no work is performed. All calendar days shall be accounted for throughout the life of the contract. Reports shall be signed and dated by the CQC system manager. The report from the CQC system manager shall include copies of test reports and copies of reports prepared by all subordinate quality control personnel.

13.1.10 Notification of Noncompliance. The Government will notify the Contractor of any detected noncompliance with the foregoing requirements. After receipt of such notice, immediate corrective action shall be taken. Such notice, when delivered to the Contractor at the site of the work, shall be deemed sufficient for the purpose of notification. If the Contractor fails or refuses to comply promptly, the Government may issue an order stopping all or part of the work until satisfactory corrective action has been taken. No part of the time lost due to such stop orders shall be made the subject of claim for extension of time or for excess costs or damages by the Contractor.

13.1.11 Technical Specifications Section Requirements. The various inspections, tests, assurances, reports, etc., called for in the various Technical Specifications Sections of SECTION C are in conjunction with this section. The CQC manager or CQC staff (also known as Contractor Quality Control Representative [CQCR]) shall conduct the inspection of all aspects of the various items mentioned in the Technical Specifications for compliance and conduct all

required inspections and tests, etc. Inspections and tests shall be recorded in the daily CQC report required in paragraph E-1.9.

13.1.12 Payment. Separate payment will not be made under this paragraph or other paragraphs in this section, all costs associated there with shall be included in the applicable unit prices or lump prices contained in the Bidding Schedule.

13.2 FINAL EXAMINATION AND ACCEPTANCE. When all the work for each unit of the equipment specified under this contract has been completed and each unit of the equipment has successfully met the requirements of the factory and field tests and has been delivered free on board (f.o.b.) destination and has been satisfactorily installed, the Government will make a through examination of the unit of the equipment and if it is found to comply with the requirements of the contract, it will be accepted and the Contractor so notified.

13.3. GOVERNMENT QUALITY ASSURANCE REPRESENTATIVE (GQAR).

The Government Quality Assurance Representatives (GQAR) have been tasked certain duties with regard to the safety provisions of the contract. None of the Contractor's responsibilities identified in Para. 01.A.02 of EM 385-1-1, the Corps Safety and Health Requirements Manual have been delegated to these employees.

(1) General Responsibility - GQAR.

(a) The GQAR will inspect contract operations for safety compliance at the same time and in the same manner as required for compliance with other terms of the contract.

(b) The GQAR will call the attention of the foreman to any violations of safe practices and will request that the unsafe condition be corrected.

(2) Action of GQAR in Case of Immediate Hazard.

(a) Whenever any GQAR observes a condition, work practice or act involving immediate hazard to workers, equipment materials or structures, or a work condition is being performed at the risk of life or limb, the GQAR will require the foreman or other contractor's representative to remove workers immediately from the area of danger, or otherwise desist from the dangerous operation or practice.

(b) In case the foreman is not at the site of the dangerous condition or operation, the GQAR will order the workers to remove themselves from the dangerous location and to cease the hazardous operation.

(c.) The GQAR will see that the work is not resumed in the area of danger and that further use of defective equipment, tools, or other facilities is not made until recommendations for correction are in full compliance.

(d) The GQAR will make an immediate report of any cessation of a dangerous operation to the GQAR's immediate supervisor.

(e) The GQAR will then follow the same procedure as outlined in paragraph (1) preceding in obtaining immediate corrective action by the Contractor; or in the event of a refusal by the Contractor to take corrective action, for a suspension of work on the contract by the Resident Engineer.

Appendix E: Technical Summary

PREPARED BY

HYDROELECTIRC DESIGN CENTER,

PORTLAND DISTRICT, COE

EROSION and CORROSION - RESISTANT

THERMAL SPRAY COATINGS

The U.S. Army Corps of Engineers' Construction Engineering Research Laboratories (CERL) has identified and developed a thermal spray coating material and process that will protect hydraulic turbine and pump water passages from damage due to erosion, cavitation resulting from erosion, and dissimilar metal corrosion damage. These surface damaging phenomena may be present to some degree in all hydraulic rotating equipment, and the repair of resulting damage depletes O&M funding and burdens the ever diminishing project maintenance staff.

The R&D program was conducted for Headquarters, U.S. Army Corps of Engineers (HQUSACE) under Construction Productivity Advancement Research (CPAR) Work Unit 3121-LY4, "Development of Cavitation/Erosion-Resistant Thermal Spray Coatings." The work was performed by CERL in partnership with the Thermal Spray Laboratory at the State University of New York (SUNY) at Stony Brook. The CERL Principal Investigator was Dr. Ashock Kumar and his assistant was Dr. Jeffrey H. Boy. The independent program technical monitory were Andy Wu, CECW-EE and Craig Chapman, CECW-OM.

The resulting R&D program report gives a good overview of hydraulic machinery water passage damage which can occur as a result of erosion, cavitation, and dissimilar metal corrosion. The report further describes current weld (fusible process) and thermal spray (non-fusible process) repair processes, and repair materials used. A valuable summary of past and current comparison testing (tests performed as a result of this R&D effort) of repair processes and materials is presented.

After an extensive literature search, consultation with academia and industry, and the laboratory testing of 21 thermal spray coatings and application methods, the report concludes that **the spray metal of choice is Stellite 6 and that the material should be applied using the High Velocity Oxyfuel (HVOF) process**. The report further details the optimal thermal spray methodology using this material and process. Laboratory tests have shown that the application of Stellite 6 results in less material loss (5.33 mm^3/h) in slurry erosion wear testing than 304 stainless steel (11.17 mm^3/h loss) and ASTM A572 carbon steel (19.70 mm^3/h loss). The change in a surface's roughness and geometry due to erosion, can result in the formation and collapse of cavitation

vapor bubbles which result in surface damage. Minimizing erosion can minimize this resulting type of cavitation. Tests also conclude that the electrical potential differences between Stellite 6 coated specimens and both ASTM A572 and A36 carbon steels in tap water were 0.25 volts, half the potential difference between 304 stainless steel and mild carbon steel (i.e., 0.50 volts). Dissimilar metal corrosion damage usually occurs at the metals interface boundary when stainless steel weld repairs are made on carbon steel water passages. It is also important to note that the thermal spray processes avoid the inducement of thermal stresses associated with the fusion welding processes.

This R&D program has shown that the current state of the art in thermal spray processes and materials cannot provide a coating that is much better in resisting cavitation damage than a carbon steel material. The report concludes that repairs required as a result of direct cavitation damage should be performed using a fusible material by a welding process. The report has shown that the spray method of surface repair is at least half the cost of welding. With this in mind, one should keep an eye on advances in this technology, as one day a material and process may be developed that will out perform carbon steel in cavitation environments.

A field test using Stellite 6 is currently underway at the Tennessee Valley Authority's (TVA) Raccoon Mountain Pumped-Storage Plant, Chattanooga, TN. Please contact Dr. Kumar, Ph. 217.373.7235, for additional information on the testing or regarding the R&D work.

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